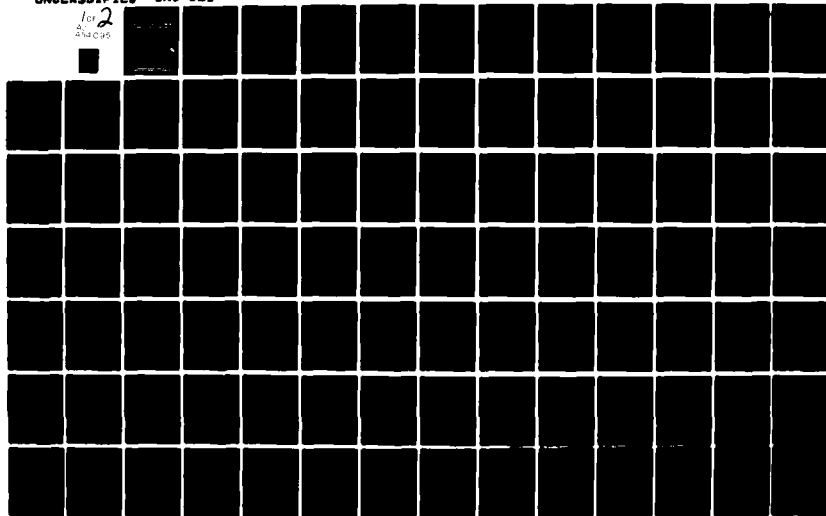


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FUEL EFFECTS ON GAS TURBINE COMBUSTORS AND ENGINES

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**FUEL EFFECTS ON GAS TURBINE
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Prepared by the

Fuel Quality Effects on Combustion and Engine

Performance and Durability Panel

of the

CRC-Aviation Group on Combustion

Characteristics of Aviation Turbine Fuels

October 1981

CRC - Aviation Fuel, Lubricant, and Equipment Research Committee

of the

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PREFACE

The Fuel Quality Effects on Combustion and Engine Performance and Durability Panel of the CRC Aviation Group on Combustion Characteristics of Aviation Fuels was established in 1978 to investigate various combustion characteristics of fuels as they relate to hardware performance and durability, and identify the major fuel-related combustor and engine problem areas.

The literature summary in this report is divided into six sections. These sections were prepared by two authors who reviewed the literature and submitted a critical digest of the applicable topics. The survey covers literature up to early 1980.

Panel members responsible for this effort are identified in Appendix A.

SECTION I

Flame Radiation, Combustor Liner Temperature, and Combustor Liner Durability (including effects of sulfur, vanadium, and other elements found in fuels derived from coal and oil shale).

Combustor liner durability is reduced as the peak liner temperature is increased. Liner temperature correlates closely with flame radiation which, in turn, correlates with fuel hydrogen content (more accurately, H/C ratio), aromatic content, aromatic ring-carbon content, smoke point, and luminometer number. Hydrogen content provides the best correlation. In some tests polycyclic aromatics produce more radiation than is predicted by hydrogen content alone, while other tests do not show any "extra" radiation effects above the hydrogen content correlation. At higher power conditions, radiation is not dependent on viscosity or volatility, so the soot formation is a gas phase process not dependent on liquid pyrolysis. Elevated pressure and inlet temperature may reduce the sensitivity to fuel effects. Reduction of the fuel hydrogen content by 1.5 percent will reduce liner life in some engines by a factor of 2.

- Bagnetto, L., and Schirmer, R.M., "Smoke Abatement in Gas Turbines - Part I: Survey of Operating Variables," Phillips Petroleum Research Report 4884-67R, ASTIA AD-845-253L, Jan. 1968.

An experimental investigation was conducted to determine the effects of operating conditions and fuel composition on exhaust smoke and flame radiation. Phillips 2-inch combustor was used to simulate the conditions for combustion found in aircraft-turbine engines. These conditions were established by controlling combustor pressure, gas velocity, heat-input rate, and inlet-air temperature; and these parameters were varied independently to study their effect. The JP-5 type fuels were selected to represent a broad range in sooting tendency, and one was treated with a smoke-suppressant additive. This survey was used in the design of an experiment for Part II of this contract, which will evaluate the relative performance of three smoke-suppressant additives in aviation-turbine fuel.

In general, our observations indicate that to reduce smoke emissions from aircraft-turbine engines (a) combustors should be operated at minimum inlet-air temperature and pressure, with maximum exhaust-gas temperature; and (b) fuels should be selected for maximum hydrogen content. At operating conditions where high smoke densities were experienced with the untreated fuel, the smoke-suppressant additive was effective in reducing exhaust smoke. On the basis of these data, the Part II study under this contract will evaluate smoke-suppressant additives at combustor operating conditions covering a broad range of inlet-air temperature and pressure while maintaining gas velocity and heat-input rate at a constant and reasonable level. Also, these additives will be evaluated in several fuels, differing as widely as possible in hydrocarbon structure.

An exploratory study to determine the effect of the addition of 0.5 per cent by weight of "Freon" FE-1301 fire-suppressant agent to aviation-

turbine fuel showed little or no change in combustion stability, combustion efficiency, flame-radiation intensity, and exhaust-smoke density.

An exploratory study to determine the effect of filter pore size when sampling exhaust-gas smoke showed little change using the AED smokemeter, with Millipore filters having pore sizes of 0.22, 0.45, 1.2 and 5 microns giving relative optical densities of 1.5, 1.3, 1.1, and 1.0. Also, a satisfactory correlation was found between AED and Von Brand smokemeters; both of which measure the "blackness" of soot filtered from the exhaust gas.

- Bagnetto, L., "Smoke Abatement in Gas Turbines- Part II: Effects of Fuels, Additives and Operating Conditions on Smoke Emissions and Flame Radiation," Phillips Petroleum Research Division Report 5127-68, ASTIA AD-842-818L, Sept 1968.

An experimental program, using Phillips 2-inch combustor to simulate the conditions for combustion found in aircraft-turbine engines, was conducted to determine the effects and interactions of fuels, additive treatments, and operating conditions on aircraft-turbine smoke emission and flame-radiation characteristics. The test program included five base fuels, selected to span a broad range in aviation-turbine fuel hydrocarbon structure, three organometallic smoke-suppressant additives (Mn, Ba, Ca), and three concentration levels of each additive. Each of the fuel-additive-concentration combinations were evaluated over a range of combustor inlet pressures of 7.5-15.0 atmospheres and combustor inlet-air temperatures of 400-1000°F, while maintaining gas velocity and the temperature rise in the combustor (about 1000°F) constant.

Analysis of the data was made by statistical procedures and the specific details and conclusions are provided. Projection of the results from mathematical relationships derived from the statistical analysis indicated the following trends: Fuel quality in terms of hydrogen content, fuel volatility and smoke-suppressant additive treatments will decrease in importance for controlling smoke emission as the severity of turbine-inlet conditions increase beyond 15 atmospheres and 1700°F. At 25 atmospheres and 2100°F the smoke emissions problem should vanish; however, a severe flame-radiation problem should be anticipated, regardless of fuel quality, fuel volatility or smoke-suppressant additives employed.

- Bagnetto, L., "Smoke Abatement in Gas Turbines - Part III: Effects of Smoke-Abatement Additives on Downstream Flame Radiation," Phillips Petroleum Research Division Report 5192-68, ASTIA AD-851-247L, Sept 1968.

An experimental program, using Phillips 2-inch combustor to simulate the conditions for combustion found in aircraft turbine engines, was conducted to determine the effects and interactions of smoke-suppressant additives and operating conditions on downstream flame-radiation intensity. The test program included a JP-5 base fuel, three organometallic smoke-suppressant additives (Mn, Ba, Ca) and three concentrations of each additive (0.012, 0.024, and 0.036 g-atoms of metal per gallon of fuel). Each of the fuel-additive-concentration combinations were evaluated over a

range of combustor inlet pressure of 7.5 - 15.0 atmospheres and combustor inlet-air temperature of 400 - 1000°F, while maintaining gas velocity and the temperature rise in the combustor constant.

The data indicate that soot in the exhaust gas acts as a screen to reduce downstream flame-radiation intensity. Since smoke-suppressant additives reduced the amount of soot in the exhaust gas, the JP-5 base fuel benefitted more from the screening effect; hence, fuels containing additives resulted in relatively higher downstream flame-radiation intensity. At conditions where soot in the exhaust gas was low, the use of Lubrizol 565 (Ba) and to a lesser extent Lubrizon 239 (Ca) showed consistent tendencies to reduce both transverse and axial (downstream) flame-radiation intensity below the performance of the base fuel, and indicates that alkaline-earth-type additives, to some degree, suppress flame radiation in the primary combustion zone. Additive concentration over the range studied had little significant effect on flame-radiation characteristics and no definite trends were indicated.

- Bert, J.A., "Review of Early Aviation Turbine Engine Liner Temperatures and Exhaust Smoke Data," Unpublished Report dated December 20, 1978, circulated to CRC Panel.

Liner temperature and exhaust smoke data from a JT-3 combustor operated on 34 petroleum test fuels of varying aromatic (0.8 - 80.5%) and hydrogen (10.9 - 15.8%) content were reevaluated. Liner temperature correlated significantly better with hydrogen content than with smoke point, luminometer number, SVI, or naphthalene content. Hydrogen content is recommended as the specification for control of liner temperature and smoke.

- Blazowski, W.S., Fahrenbruck, F.S., and Tackett, L.P., "Combustion Characteristics of Oil Shale Derived Jet Fuels," Paper 75-13, Western States Section/Combustion Institute, Oct 1975.

T56 combustor rig tests were conducted on JP4 and JP5 fuels derived from oil shale. Liner temperature and gaseous emissions were measured. The JP4 oil shale fuel was also evaluated in the J85-5 engine. General performance and emissions parameters were measured. Finally a T39 aircraft fueled with the clay treated, shale oil derived JP4 was flown as part of the evaluation.

- Blazowski, W. S., "Combustion Considerations for Future Jet Fuels," Sixteenth (International) Combustion Symposium, Boston, Aug 1976, the Combustion Institute.

T56 combustor rig tests were performed with test fuels consisting of JP4/Xylene blends (12.7 to 14.5 percent hydrogen by weight), high fuel bound nitrogen blends, and two oil shale derived JP4 fuels.

Increases of combustor liner temperature with decreased fuel hydrogen content were found to be substantial. A new, non-dimensional temperature parameter is presented which provides an excellent means of correlating results for combustors having rich primary zones designs. Limited data for

new low-smoke lean designs indicate much less sensitivity of combustor liner temperature to fuel hydrogen content.

- Blazowski, W.S., and Jackson, T.A., "Evaluation of Future Jet Fuel Combustion Characteristics," AFAPL-TR-77-93, July 1978.

The impact of lower fuel hydrogen content on combustor liner temperatures, smoke, and gaseous emissions has been evaluated and improved correlations with hydrogen content have been developed. Results obtained with the various fuel blends tested have confirmed the dominant influence of hydrogen content on combustion characteristics when compared to volatility and hydrocarbon type effects.

Use of the new non-dimensional liner temperature parameter has also resulted in a good correlation of a wide variety of previous combustor data involving rich combustion systems. However, comparison with data obtained using low-smoke combustor design indicated that newer designs having airblast fuel injection and leaner combustion may be much less sensitive to fuel hydrogen content.

The effectiveness of a smoke abatement fuel additive and a lean combustor primary zone have also been investigated. The additive reduced smoke emission but not liner temperature while the lean primary zone resulted in lower liner temperatures but no significant smoke emission decrease.

- Blazowski, W.S., "Dependence of Soot Production of Fuel Blend Characteristics and Combustion Conditions," ASME Paper 79-GT-155.

Decreased fuel hydrogen content resulting from an increased aromatic content has been observed to result in increased exhaust smoke and particulates as well as greater flame luminosity. This paper contributes empirical information and insight which allows the greater soot formation tendencies of low hydrogen content fuels to be better understood. A small scale laboratory device which simulates the strongly black-mixed conditions present in the primary zone of a gas turbine combustor is utilized. These results have been analyzed to develop useful correlations which are in general agreement with existing mechanistic concepts of the soot formation process.

- Butze, H.F., and Ehlers, R.C., "Effect of Fuel Properties on Performance of a single Aircraft Turbojet Combustor," NASA TM X-71789, Oct 1975.

The performance of a single-can JT8D combustor was investigated with a number of fuels exhibiting wide variations in chemical composition and volatility. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons and NO_x , as well as liner temperatures and smoke. At the simulated idle condition no significant differences in performance were observed. At cruise, liner temperatures and smoke increased sharply with decreasing hydrogen content of the fuel. No significant differences were observed in the performance of an oil-shale derived JP-5 and a petroleum-based Jet A fuel except for emissions of NO_x which were higher with the oil-shale JP-5.

- Butze, H.F., and Liebert, C.H., "Effect of Ceramic Coating of JT8D Combustor Liner on Maximum Liner Temperatures and Other Combustor Performance Parameters," NASA TM X-73581, December 1976.

The effect of ceramic coating of a JT8D combustor liner was investigated at simulated cruise and takeoff conditions with two fuels of widely different aromatic contents. Substantial decreases in maximum liner temperatures and flame radiation values were obtained with the ceramic-coated liner. No deterioration of the ceramic coating was observed after about 6 hours of cyclic operation including several startups and shutdowns.

- Butze, H.F., and Smith, A.L., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor at Simulated Idle, Cruise, and Takeoff Conditions," NASA TM-73780, Sept 1977.

The performance of a single-can JT8D combustor was investigated with a number of fuels exhibiting wide variations in chemical composition and volatility. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons and NO_x, as well as liner temperatures and smoke. The most pronounced effects of changes in fuel composition were observed at simulated cruise and takeoff conditions where smoke and liner temperatures increased significantly, as the hydrogen content of the fuel decreased.

- Butze, H.F., Humenik, F.M., "Parametric Performance of a Turbojet Engine Combustor Using Jet A and a Diesel Fuel," NASA-TM-79089, March 1979.

The performance of a single-can JT8D combustor was evaluated with Jet A and a high-aromatic diesel fuel over a parametric range of combustor-inlet conditions. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons, and NO_x, as well as liner temperatures and smoke. At all conditions the use of diesel fuel instead of Jet A resulted in increases in smoke numbers and liner temperatures; gaseous emissions, on the other hand, did not differ significantly between the two fuels.

- Clark, J.A., et al., "Radiation/Smoke and Combustion Efficiency from Gas Turbine Flames, IV. Fuel Property Effects on Performance," PURDU-CL-79-05, March 1979. (USATARADCOM DAAE07-76-C-0063, Technical Report No. 12438).

The performance of gas turbine combustors with respect to combustion efficiency, flame stabilization, ignition, smoke and radiation, burning a wide range of fuel types is considered. The experimental portion of the program was conducted with a simplified combustor designed to yield apparatus independent results.

Experimental results are provided for radiation and smoke measurements. These results include radiation intensity and emissivity measurements from two fuels, smoke mass concentrations and particle size measurements at various locations inside the combustor. Theoretical calculations based on the smoke data significantly underpredict the actual flame radiation.

- Colket, M.B., et al., "Radiation and Smoke from Gas Turbine Flames, Part II: Fuel Effects on Performance," PURDU-CL-77-01, 1977. (USATACOM DAAE07-76-C-0063)

Fuel effects upon gas turbine combustor performance, including combustion efficiency, lean blow off, smoke, and flame radiation, must be defined to minimize developmental efforts in adapting existing Army engines to synthetic and alternate fuels. Preliminary flame radiation measurements have been obtained.

- Detroit Diesel Allison, "Model 501-K17 Gas Turbine Single Burner Evaluation of Shale Derived Marine Diesel Fuel," DDA EDR 8660, Jan 1976.

A significant quantity of crude oil has been extracted from Colorado oil shale in the Paraho project. This crude was subsequently experimentally refined to produce a broad range of military fuels. This report presents results obtained in gas turbine combustion tests of a marine diesel fuel from this project. A can-annular segment of the DDA 501-K17 marine gas turbine engine was used in the tests. Burner conditions simulated the operating spectrum experienced by this engine in the U.S. Navy DD963 class destroyers. Starting and steady state points from zero to full power were examined. The performance of the shale fuel was compared with that obtained at equivalent conditions with a petroleum marine diesel fuel from the U.S. Navy supplies. No tendencies toward increased carbon deposition or liner wall temperature elevation were indicated in these limited duration tests.

- Ekstedt, E.E., and Macaulay, R.W., "Combustion of Heavy Distillate Fuel for the LM2500 Gas Turbine," ASME 72-GT-24, Jan 1973.

The LM2500 is a Marine and Industrial gas turbine derived from the TF39 engine built for the USAF C5A transport. As such it operates as a core engine without the high bypass fan supercharging effect. The combustor for the LM2500 is an annular combustor developed for the use with marine and industrial fuels including natural gas and heavy distillates. This paper relates the development of this combustor including some of the design criteria, the fuel properties and some of the combustor performance results such as exit gas temperature patterns, ignition, pressure loss, and efficiency. The engine combustor operates with a clear smokeless stack utilizing heavy distillate fuels and is free of carbon formation. Fuel properties and atomization properties are related to exhaust smoke. Investigations have included a wide range of fuels and several fuel injector designs. The engine has operated in GTS Adm. Wm. M. Callaghan for a total of more than 10,000 hrs with no combustor problems, smoke, carbon, life or otherwise.

- Ferguson, C.R., and Mellor, A.M., "Radiative Heat Transfer from Gas Turbine Flames," ASME Paper 79-GT-144, March 1979.

Measurements have been made of the normal component of the radiative heat flux to the wall of a model gas turbine combustor with and without a mirrored background. Measurements have also been made of the centerline soot concentration. The data show that the heat flux correlated with the soot concentration but not universally, since JET A fuel yielded a different curve than DIESEL fuel. A theoretical analysis of the heat flux

from a soot suspension was formulated. A criterion was established for the use of a small particle analysis. Finally, it is shown that there is no correspondence between theory and these experiments. It is speculated that turbulent fluctuations need to be modeled.

- Friswell, N.J., "The Influence of Fuel Composition on Smoke Emission from Gas-Turbine-Type Combustors: Effect of Combustor Design and Operating Conditions," Combustion Science and Technology, 19, 119 (1979).

The influence of fuel composition on smoke emission/combustor wall temperatures has been studied in a laboratory-scale gas-turbine-type combustor over the range of operating conditions of modern turbine combustors and as a function of combustor design. Fuel hydrogen content is shown to give the best prediction of smoke emission and of variations in flame tube wall temperature caused by changes in flame radiation. The major finding is that the influence of fuel composition on smoke emission/flame radiation falls virtually to zero at combustor pressures above about 10 bar. Significant reduction in sensitivity to fuel composition can also be obtained by varying combustor design and are tentatively correlated with increasing combustion intensity. The implication of these effects for aircraft operation is discussed and an explanation for the results is put forward based on changes in the chemical mechanisms leading to soot formation.

- Gleason, C.C., and Bahr, D.W., "Alternate Fuels Addendum, Phase II. Experimental Clean Combustor Program," NASA CR-134972, Jan 1976.

A study was conducted to investigate the characteristics of current and advanced low-emissions combustors when operated with special test fuels simulating broader ranges of combustion properties of petroleum or coal-derived fuels. Five fuels were evaluated; conventional JP-5, conventional No. 2 Diesel, two different blends of Jet A and commercial aromatic mixtures- "xylene bottoms" and "naphthalene charge stock", and a fuel derived from shale oil crude which was refined to Jet A specifications. Three CF6-50 engine size combustor types were evaluated; the standard production combustor, a Radial/Axial Staged Combustor, and a Double Annular Combustor. Performance and pollutant emissions characteristics at idle and simulated takeoff conditions were evaluated in a full annular combustor rig. For the five fuels tested, effects were generally quite moderate, but well defined. CO, HC, NO_x and smoke emissions levels and peak liner metal temperatures increased with decreasing hydrogen content of the fuel which ranged from 12.2 to 13.7 percent by weight.

- Gleason, C.C., Bahr, D.W., "Experimental Clean Combustor Program: Diesel No. 2 Fuel Addendum, Phase 3," NASA-CR-135413, May 1979.

A CF6-50 engine equipped with an advanced, low emission, double annular combustor was operated 4.8 hours with No. 2 diesel fuel. Fourteen steady-state operating conditions ranging from idle to full power were investigated. Engine/combustor performance and exhaust emissions were obtained and compared to JF-5 fueled test results. With one exception,

fuel effects were very small and in agreement with previously obtained combustor test rig results. At high power operating condition, the two fuels produced virtually the same peak metal temperatures and exhaust emission levels. At low power operating conditions, where only the pilot stage was fueled, smoke levels tended to be significantly higher with No. 2 diesel fuel.

- Gleason, C.C., et. al., "Evaluation of Fuel Character Effects on the J79 Engine Combustion System," AFAPL-TR-79-2015, June 1979.

Results of a program to determine the effects of broad variations in fuel properties on the performance, emissions, and durability of the J79-17A turbojet engine combustion system are presented. Combustor tests conducted at engine idle, takeoff, subsonic cruise, supersonic dash, cold day ground start, and altitude relight operating conditions with 13 different fuels are described. The test fuels covered a range of hydrogen contents (12.0 to 14.5 percent), aromatic type (monocyclic and bicyclic), initial boiling point (285 to 393 K), final boiling point (552 to 679 K) and viscosity (0.83 to 3.25 mm²/s at 300 K).

At high power operating conditions, fuel hydrogen content was found to be a very significant fuel property with respect to liner temperature, flame radiation, smoke, and NO_x emission levels. Combustor liner life analyses, based on the test data, yielded relative life predictions of 1.00, 0.78, 0.52, and 0.35 for fuel hydrogen contents of 14.5, 14.0, 13.0, and 12.0 percent, respectively. Turbine life was predicted to be unaffected by any of the fuels tested.

- Gleason, C.C., et al, "Evaluation of Fuel Character Effects on F101 Engine Combustion System, Final Report," AFAPL-TR-79-2018, June 1978.

Results of a program to determine the effects of broad variations in fuel properties on the performance, emissions and durability of the General Electric F101 augmented turbofan engine main combustion system are presented. Combustor rig tests conducted at engine idle, takeoff, cruise, dash, cold day ground start and altitude relight operating conditions with 13 different fuels are described. Fuel nozzle fouling tests conducted with the same fuels are also described. The test fuels covered a range of hydrogen contents (12.0 to 14.5%), aromatic type (monocyclic and bicyclic), initial boiling point (285 to 393 K), final boiling point (552 to 679 K) and viscosity (0.83 to 3.25 mm²/s at 300 K).

At high power conditions, fuel hydrogen content was found to have a very significant effect on liner temperature, smoke, and NO_x levels. While smoke levels decreased with increasing hydrogen content, the levels were very low with all the fuels. Combustor liner life analyses yielded relative life predictions of 1.00, 0.72, 0.52, and 0.47 for fuel hydrogen contents of 14.5, 14.0, 13.0, and 12.0 percent, respectively. At the present state of turbine stator development, no fuel effect on life is predicted.

- Gleason, C.C., and Bahr, D.W., "Fuel Property Effects on Life Characteristics of Aircraft Turbine Engine Combustors," ASME 80-GT-55, 1980.

Results of a program to determine the effects of fuel properties on the life characteristics of two USAF/General Electric aircraft turbine engine combustors are presented. Thirteen test fuels were evaluated in an older technology cannular combustion system (J79) and in an advanced technology, virtually smokeless, compact, annular combustion system (F101) over wide ranges of simulated engine operating conditions. Fuel variables were hydrogen content, aromatic structure, volatility and distillation end point. Significant increases in combustor liner temperatures were observed as fuel hydrogen content was decreased. With fuel hydrogen contents of 14.5, 14.0, 13.0 and 12.0, the resulting relative combustor liner cyclic life predictions are 1.00, 0.78, 0.52 and 0.35 for the J79 combustor and 1.00, 0.72, 0.52 and 0.47 for the F101 combustor, respectively. Based on these findings, it is concluded that improved liner cooling design features will be needed in most current technology combustors to accommodate the projected lower hydrogen contents of future fuels.

- Gleason, C.C., and Martone, J.A., "Fuel Character Effects on J79 and F101 Engine Combustor Emissions," ASME 80-GT-70, 1980.

Results of a program to determine the effects of fuel properties on the pollutant emissions of two US Air Force aircraft gas turbine engines are presented. Thirteen test fuels, including baseline JP-4 and JP-8, were evaluated in a cannular (J79) and a full annular (F101) combustor. The principal fuel variables were hydrogen content, aromatic structure, volatility, and distillation end point. Data analysis shows that fuel hydrogen content is a key fuel property, particularly with respect to high power emissions (oxides of nitrogen and smoke), and that low power emissions (carbon monoxide and hydrocarbons) are more dependent on fuel atomization and evaporation characteristics.

- Goodger, E.M., and Najjar, Y.S.H., "Heavy-fuel Flame Radiation in Gas Turbine Combustors - Exploratory Results," Fuel, 56, 437, (1977).

With lower costs and greater availability, heavy fuel oil appears as an attractive alternative to the conventional gas oil used in industrial gas turbines. However, higher levels of radiation and smoke are expected, and this note reports on some preliminary tests made with a combustion chamber burning fuels of different carbon content, ranging from kerosene to a 25% blend of residual fuel oil in gas oil, at a chamber pressure of 10 atm. The combustion rig was equipped with a total-radiation pyrometer and black-body furnace capable of measurement at different axial stations along the spray-stabilized flame. The presence of the residual fuel oil in the gas oil was found to promote significant increases in the mean levels of radiation, emissivity and smoke density, with a modest increase in liner temperature.

- Hammond, D.C., "Operation of a GT-225 Diffusion-Flame Combustor on Alternative Fuels Performance, Durability and Emissions," ASME Paper No. 79-GT-138, 1979.

Ten fuels were burned in a GT-225 diffusion-flame combustor and the performance, durability, and emissions evaluated. These fuels were: reference kerosene, three petroleum distillates, two alcohols, one coal-

derived fuel, a fuel made from tar sands, and two fuels made from oil shale. All of the fuels were burned without modifying either combustor or fuel nozzle. The more volatile petroleum distillates burned more efficiently than kerosene. The alcohols and the more viscous synthetic fuels exhibited combustion efficiencies slightly lower than that of kerosene, possibly as a result of poorer initial atomization. The synthetic fuels having high aromatic contents produced higher flame-tube-wall temperatures than did kerosene, but not sufficiently high to reduce durability.

- Horstman, W.W., and Jackson, J.L., "Combustion Characteristics of Special Hydrocarbon Jet Fuels," ASD TDR-62-682 WPAFB, 1962.

A single combustor from a General Electric J-79 engine was used to evaluate combustion efficiency, flame radiation, fuel consumption, and altitude relight characteristics of twelve hydrocarbon fuels. Selection of fuels was based primarily on heat of combustion, density, Luminometer Number, and thermal stability for potential use in supersonic aircraft gas turbine engines. Tests were made with simulated Mach 1.5, 2, 2.5, and 3 speeds at 80,000 feet altitude, and a higher combustor severity condition at the maximum compressor output.

Combustor metal temperature was directly proportional to the combined effect of heat conduction and convection and flame radiation. At a given test condition, differences in fuel composition caused variations in liner temperature and flame total radiation which became greater as the combustion intensity increased. At high heat release rates, liner temperatures were reduced significantly with paraffinic type fuels. The liner temperatures correlated equally well with hydrogen/carbon ratio and with Luminometer Number. Hydrogen/carbon ratio is preferred on the basis of simplicity and reliability.

- Hubbard, E.H., "Comparison of Different Methods of Fluid-Atomizing Oil Flames and the Effect on Flame Emissivity and Radiation of the Addition of Carbon Black to Liquid Fuels," Journal of The Institute of Fuel, p. 338, July 1959.

In these experiments a 50/50 suspension of carbon black in fuel oil was added in turn to a gas oil and a fuel oil. The effect on turbulent jet diffusion flames burning these mixtures was to increase the flame emissivity at a fixed distance from the burner roughly in proportion to the increase in C:H ratio. The increase seemed more pronounced at the tail of the flame. In the case of fuel oil there are technical difficulties in keeping more than about 6 per cent of carbon by weight in suspension for long periods and in industrial practice it is usual to inject the carbon as near to the burner as possible.

- Jackson, T.A., and Blazowski, W.S., "Fuel Hydrogen Content as an Indicator of Radiative Heat Transfer in an Aircraft Gas Turbine Combustor," AFAPL-TR-79-2014, Feb 79.

Fuel blends with hydrogen content ranging from 9.9 to 15.9 percent by weight were evaluated in a T56 single can combustor rig. Blends were

formulated with different types of hydrocarbon compounds. A second order correlation of the liner temperature data is formulated and compared with an expression derived from a simplified radiation analysis. Agreement is excellent between the empirical and analytical equations.

- Jackson, T.A., and Blazowski, W.S., "Fuel Hydrogen Content as an Indicator of Radiative Heat Transfer in an Aircraft Gas Turbine Combustor," Gas Turbine Combustion and Fuels Technology, Winter Annual Mtg. ASME, Dec 1977.

Eleven fuels representing a wide range of hydrogen content were studied using a T56 single can combustor rig. Test fuels included single and double ring aromatic types as well as paraffins blended with each other and with JP-4. Fuel mixtures with hydrogen contents ranging from 9.9 to 15.9 per cent by weight were examined. The combustor inlet conditions simulated the discharge from both low and high pressure ratio gas turbine compressors operating at the cruise condition. Thermocouple data from the T56 liner are correlated with fuel hydrogen content using a new, non-dimensional combustor liner temperature parameter. Least-squares mathematical treatment of the data resulted in an excellent second order correlation between the non-dimensional temperature parameter and fuel hydrogen content and a simplified radiation analysis is presented which also explains the resulting empirical trends.

- Kittredge, G.D., "Gas Turbine and Jet Engine Fuels," Progress Report No. 1, Navy Contract N0as 60-6009-c, Phillips Petroleum Co. Res. Div. Report 2508-59R, 1959.

Effects of monocyclic versus polycyclic aromatic structures in JP-5 fuels of equal ASTM Smoke Point level were studied using a full scale and laboratory scale single combustors along with several bench scale lamp test procedures.

Results with a single J57 combustor operated at a pressure approaching 5 atmospheres showed very measurable differences in flame radiant heating of the combustor liner surface due to variations in fuel composition. Blends containing polycyclic aromatics had somewhat more adverse effects than equal smoke point blends with monocyclic aromatics. Visual brightness of the J57 combustor flames was only a rough guide to total radiant heat emitted.

The Phillips 2-inch combustor flame radiation intensities of 5 atmospheres pressure correlated quite well with the J57 results, though the adverse effects of polycyclic aromatics were not "seen" by the 2-inch combustor at this condition. In contract, the 2-inch combustor tests at 15 atmospheres pressure correlated much less well with the J57 results, but here the polycyclic aromatics (on an averaged basis) did show up more poorly than the monocyclic aromatic compounds.

Tests at close to 1 atmosphere pressure in a J79 full scale single combustor and in the Phillips Microburner showed no significant differences between any of the fuels tested in flame radiant heating effects. However somewhat heavier microburner deposit laydown was observed with the polycyclic aromatic blends.

Three bench scale lamp test procedures, ASTM Smoke Point, Standard of Indiana Smoke Point and CRC Luminometer, all agreed in general with the trends shown in the J57 combustor. The latter two procedures would accommodate the complete range in fuel quality represented by these test fuels and, in addition, appeared slightly more sensitive to polycyclic aromatics.

- Kittredge, G.D. and Streets, W.L., "Gas Turbine and Jet Engine Fuels," Summary Report Navy Contract NOas 60-6009-c, Phillips Petroleum Co. Res. Div. Report 2760-60R, Feature No. 6040, 1960.

Cooperative tests conducted by Phillips, Navy Aeronautical Engine Laboratory and others exploring the role of fuel composition on flame radiant heating of jet combustor metal surfaces have indicated an almost linear relationship between total flame radiant heat emission from J57 single combustor flames at about 5 atmospheres pressure and metal temperatures along the combustor liner. JP-5 fuel blends of constant smoke point containing polycyclic as opposed to monocyclic aromatic compounds produced somewhat more intense radiant heating in the J-57 combustor. Phillips Microburner tests at atmospheric pressure showed no differences in flame radiation among these fuels; however, in terms of combustion zone deposits JP-5 blends containing polycyclic aromatics performed somewhat more poorly at any given smoke point level than those containing only monocyclic aromatic compounds.

Two-inch combustor tests carried out to investigate the effect of fuel sulfur type and concentration on flame tube durability have shown that slight differences observed among eight sulfur compounds used as artificial fuel contaminants at constant total sulfur levels fall within the repeatability band of the test method and apparatus used. Thus the individual sulfur compounds did not vary appreciably in their effects on flame tube durability and gross sulfur concentration, rather the form in which the sulfur existed, defined the degree of deterioration.

- Kretschmer, D., Odgers, J., "Simple Method for the Prediction of Wall Temperatures in Gas Turbines," ASME Paper 78-GT-90, 1978.

The cited method predicts wall temperatures generally within an accuracy of ± 6 percent. The biggest single factor governing the wall temperature is shown to be the hot gas temperature. Other factors discussed are the effects of changes in inlet temperature, fuel types, the geometry of the film cooling devices and manufacturing tolerances. Empirical formulas are given for the prediction of effective temperatures within the various combustor zones. Some comparisons are made between predictions and measurements of wall temperatures over a range of operating conditions.

- Lohmann, R.P., Szetela, E.J., Vranos, A., "Analytical Evaluation of the Impact of Broad Specification Fuels on High Bypass Turbofan Engine Combustors," NASA CR-159454, PWA 5565-15, Dec 1978.

The impact of the use of broad specification fuels on the design, performance durability, emissions and operational characteristics of

combustors for commercial aircraft gas turbine engines was assessed. Single stage, vorbix and lean premixed prevaporized combustors, in the JT9D and an advanced energy efficient engine cycle were evaluated when operating on Jet A and ERBS (Experimental Referee Broad Specification) fuels. Design modifications, based on criteria evolved from a literature-survey, were introduced and their effectiveness at offsetting projected deficiencies resulting from the use of ERBS was estimated. The results indicate that the use of a broad specification fuel such as ERBS, will necessitate significant technology improvements and redesign if deteriorated performance, durability and emissions are to be avoided. Higher radiant heat loads are projected to seriously compromise liner life while the reduced thermal stability of ERBS will require revisions to the engine-airframe fuel system to reduce the thermal stress on the fuel. Smoke and emissions output are projected to increase with the use of broad specification fuels. While the basic geometry of the single stage and vorbix combustors are compatible with the use of ERBS, extensive redesign of the front end of the lean premixed prevaporized burner will be required to achieve satisfactory operation and optimum emissions.

- Macaulay, R.W., and Shayeson, M.W., "Effects of Fuel Properties on Liner Temperatures and Carbon Deposition in the CJ805 Combustor for Long-Life Applications.", ASME 61-WA-304, Oct 1962.

Extensive flight test of the CJ805 engine has demonstrated durability characteristics for the combustor with fuels of marginal quality. Efforts to increase this durability by reducing liner temperatures and carbon deposition have resulted in improved designs. During the past two years, single-can combustion tests have been undertaken in a co-operative program with Texaco Research Center at Beacon, N.Y., to evaluate carbon formation and liner temperatures with various liquid fuels. These results have been correlated with factory engine tests and General Electric component combustion tests with resulting improvements in liner cooling and carbon formation.

- Marchionna, N. "Turbine Fuel Tolerance Study: Multifuel Engine Tests," USATARADCOM Technical Report 12392 (DAAE07-74-C-0274) July, 1978.

An AGT 1500 vehicular gas turbine engine was tested for multifuel capability. Overall performance did not vary when operating on JP-4, DF-2, or unleaded gasoline. Smoke and combustor liner wall temperatures were highest with gasoline and lowest with JP-4. These effects are attributed to a more luminous flame as a result of higher aromatic content in the gasoline.

- Marsland, J., Odgers, J., and Winter, J., "The Effects of Flame Radiation on Flame-Tube Metal Temperatures," Twelfth Symposium (International) on Combustion, 1969, the Combustion Institute.

Details are given of experiments to determine flame radiation, Red Brightness temperatures and metal temperatures in the primary zones of three aircraft combustion chambers; flame temperatures and emissivities are derived.

These factors were studied using two pipe chambers (3.75 in. and 5.625 in. diam) over a range of pressures from 4-30 atm and a nominal air-inlet temperature and air/fuel ratio of 800°K and 60/1, respectively. The indications were that flame radiation, temperature, and emissivity increased with pressure, whereas metal temperatures indicated a similar trend, attributed to the convective cooling that increased at a greater rate than flame radiation at the higher pressures.

The effects of vitiation and subsequent oxygen replenishment were examined using a tubo-annular combustion chamber operating at a pressure of 4 atm, inlet temperature 777°K, and a nominal air/fuel ratio of 63/1. Primary-zone flame radiation, flame temperature, and metal temperature increased with the oxygen content of the inlet gas. No similar trend was noted with flame emissivity.

- Martel, C.R., and Angello, L.C., "Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels," AFAPL-TR-72-103, May 1973.

Results of statistical correlations of fuel data are presented wherein the hydrogen content of fuels is correlated with other fuel combustion measurements including smoke point, luminometer number, and net heat of combustion. Results indicate that for a certain range of fuels knowing a fuel's hydrogen content eliminates the need to evaluate its smoke point, luminometer number or its net heat of combustion.

- McClelland, C.C., "Effects of Jet Fuel Constituents on Combustor Durability," Report NAEC-AEL-1736, AD 404 084, 1963.

Liner temperatures and flame radiation intensity in a J79 combustion chamber are functions of both the luminometer number and the hydrogen content of the fuel. As liner temperature tends to level out above a luminometer number of 100 there is little to be gained from further increase in this parameter.

An increase in J79 combustor inlet air temperature will result in increases in flame radiation and in the liner temperature rise above inlet air temperature. The relationships with luminometer number are similar to those at lower temperature.

Both luminometer number and hydrogen content of a fuel will provide satisfactory correlations with flame radiation and liner temperatures for future higher combustor inlet temperature conditions.

Liner temperatures in a jet engine combustor are directly proportional to the intensity of the total flame radiation received by the liner. The position and intensity of the flame zone and the maximum liner temperature will vary with differences in combustor design and fuel type at a given set of operating conditions.

A fuel containing polycyclic aromatic hydrocarbons will give higher flame radiation intensity and liner temperatures than a fuel containing an equal percentage of monocyclic aromatic hydrocarbons. This fact can be attributed to the differences in hydrogen content of the two aromatic types and is reflected in the differences in luminometer number.

2. Moses, C.A., and Naegeli, D.W., "Effects of High Availability Fuels on Combustor Properties," AFLRL Report No. 101, AD-A054229, Jan 1978.

A high pressure and temperature research combustor was operated over a matrix of conditions involving

- a) burner inlet pressure, BIP = 2, 5, 10 and 15 atm,
- b) burner inlet temperature, BIT = 532, 812 and 1034°K,
- c) fuel/air ratio (heat input rate), H = 212, 424 and 848 KJ/Kg of air, and
- d) reference velocity (turbulence and residence time), V = 22, 44 and 66 M/sec.

Six petroleum base JP-5 fuels (principally aromatic blends) and three JP-5 syncrudes (from oil shale, coal and tar sands) were examined. Flame radiation and exhaust smoke from petroleum based fuels correlated equally well with fuel hydrogen, aromatics and ring carbon. The radiation and smoke from the syncrude fuels correlated best with hydrogen content. The oil shale and tar sand derived fuels behaved similarly to petroleum base fuels while the syncrude from coal gave relatively higher radiation and smoke based on its hydrogen content. Flame radiation and exhaust smoke were relatively insensitive to fuel at low levels of radiation and smoke, but at higher levels, the fuel sensitivity increased significantly.

2. Moses, C.A., and Naegeli, D.W., "Fuel Property Effects on Combustor Performance," ASME 79-GT-178, 1979.

Two combustor rigs have been used to study the sensitivity of combustor performance to the physical and chemical properties of fuels. The purpose was to determine the impact of broadening fuel specifications and using non-specification fuels in emergencies. Nineteen fuels including synfuels were used to accentuate the properties of concern: composition, viscosity, and boiling point distribution. The combustors were instrumented for flame radiation, liner temperature, and exhaust emissions; testing included ignition, stability, and combustion efficiency.

Hydrogen content was the most effective correlating parameter for radiation and smoke; sensitivities to hydrocarbon structure were secondary. The syncrude fuels correlated the same way as the petroleum fuels. Higher end points did not affect the correlation, indicating the soot formation was due to gas-phase reactions not liquid-phase pyrolysis. Results indicate clean-burning combustors should have low sensitivity to hydrogen content.

2. Naegeli, D.W., and Moses, C.A., "Effects of Fuel Properties on Soot Formation in Turbine Combustion," SAE Paper No. 781026, 1978.

A T-63 combustor rig has been used to study the sensitivity of combustor performance to the physical and chemical properties of fuels. The purpose was to determine the impact of broadening fuel specifications and using non-specification fuels in emergencies. The fuel properties of special concern were the composition, the distillation curve and viscosity.

The first property is associated with the chemistry of carbon formation while the latter two are related to mixing as they affect the atomization and vaporization. The combustor was instrumented for flame radiation, exhaust smoke, and gaseous emissions. Measurements of these items were made at the full power condition. The hydrogen/carbon ratio was the most effective correlating parameter for radiation and smoke; sensitivities to molecular structure appeared to be secondary. Similar to the syncrude fuels, the water/fuel emissions and methanol/aromatic blends correlated in the same way as petroleum fuels. Higher end points did not affect the correlation indicating that soot formation was due to gas phase reactions, not liquid phase pyrolysis. The results favor a chemical mechanism for the role of water in reducing soot.

- Naegeli, D.W., and Moses, C.A., "Effect of Fuel Molecular Structure on Soot Formation in Gas Turbine Engines," ASME 80-GT-62, March 1980.

A high-pressure research combustor operating over a wide range of burner inlet conditions was used to determine the effects of fuel molecular structure on soot formation. Six test fuels with equal hydrogen content (12.8%) were blended to stress different molecular components and final boiling points. The fuels containing high concentrations (20%) of polycyclic aromatics and partially saturated polycyclic structures such as tetralin, produced more soot than would be expected from a hydrogen content correlation for typical petroleum based fuels. However, fuels containing naphthenes such as decalin agreed with the hydrogen content correlation. The contribution of polycyclic aromatics to soot formation was equivalent to a reduction in fuel hydrogen content of about one percent. The fuel sensitivity to soot formation due to the polycyclic aromatic contribution decreased as burner inlet pressure and fuel/air ratio increased.

- Norster, E.R., and Lefebvre, A.H., "Influence of Fuel Preparation and Operating Conditions on Flame Radiation in a Gas Turbine Combustor," ASME 72-WA/HT-26, 1972.

A tubular, aircraft-type combustor is operated over wide range of conditions in order to examine the influence on flame radiation of variations in pressure, air/fuel ratio and reference velocity. Both dual orifice and airblast atomizers are investigated in order to assess the effect of fuel preparation on flame radiation. The results confirm the findings of previous workers in regard to the effects pressure and air/fuel ratio with the dual orifice atomizer. The same trends are also observed with the airblast atomizer but the absolute levels of flame radiation are appreciably less. Flame radiation is found to diminish with increase in combustor velocity, especially with the airblast atomizer. This suggests that for minimum flame radiation combustors should employ airblast atomization and operate at the highest possible reference velocity.

- Patarini, V., Bornstein, N.S., and DeCrescente, M.A., "Hot Corrosion of Gas Turbine Components," ASME 78-GT-82, 1978.

Hot corrosion is the accelerated rate of oxidation of coatings and substrates, which occurs when a condensed phase is present on the surface.

The major constituent of the corrosive deposit is sodium sulfate, although when fuels other than light distillates are employed, the deposit can contain various amounts of vanadium pentaoxide, an impurity present in many heavy distillates and most residual oils. Other corrodents that can be present in varying concentrations are lead, carbon and alkali halides. The coatings employed to extend the life of gas turbine alloys, and the alloys themselves exhibit varying degrees of resistance to hot corrosion. In our study of the "Parameter Monitoring for Corrosion Control of Utility Gas Turbines" we are determining the relative effect of each of the aforementioned corrodents with respect to simple aluminides, overlay coatings and precious metal coatings on three nickel base superalloys and one cobalt base superalloy. Although these studies are being conducted over the temperature range from 1500 to 1800°F, this presentation primarily emphasizes the completed high temperature results with some examples of the ongoing lower temperature studies.

- Pillsbury, P.W., et al., "Investigating Combustion Turbine Burner Performance with Coal Derived Liquids Having High Fuel Bound Nitrogen," ASME 78-GT-126, 1978.

The problems of fueling standard units with these liquids are being determined, with special emphasis on environmental aspects. Small-scale and full-scale laboratory combustor tests are described. Results from earlier tests are surveyed, especially with regard to smoke production, NO_x emissions, and flame radiation. A unique feature of the present program is the stress of developing surrogate petroleum-derived fuel to "stand-in" for scarce coal liquids during early development of the advanced burners needed to handle a broad range of coal liquids.

- Pillsbury, P.W., et al., "Fuel Effects in Recent Combustion Turbine Burner Tests of Six Coal Liquids," ASME 79-GT-137, 1979.

Comparative tests have been made in combustion turbine burners between six coal derived liquid (CDL) fuels and No. 2 distillate oil. All CDL fuels were evaluated in a half-scale (by diameter) combustor test rig, while one CDL fuel was also evaluated in a full scale high pressure combustion rig. The effects of these fuels on emissions of smoke and oxides of nitrogen, and on combustor metal temperature are discussed. Also observed in the testing were flame radiation, post-test combustor cleanliness, and emissions of carbon monoxide and hydrocarbons. Two of the CDLs do appear to be within the tolerance band which present combustion turbines can accept with the exception of elevated NO_x emissions.

- Plee, S.L., et al., "Radiation and Smoke from Gas Turbine Flames Part III," Technical Report No. 12349, March 1978.

Combustion efficiency, lean blowoff, smoke, flame radiation and spark ignition characteristics of gas turbine type flames are examined with particular emphasis on effects of alternate and synthetic fuels. Using a semi-empirical modeling technique, combustion efficiency and flame stabilization results have been linearly correlated for flames in which

heterogeneous effects are negligible (light fuels). Modeling parameters include variations in combustor pressure, inlet temperature, geometry, air flow rate and reference velocity. This technique, which has proven successful in correlating combustion efficiency data from helicopter and automotive gas turbines, should also be applicable to the Army AGT-1500 engine for the XM-1 Main Battle Tank. The effect of fuel properties (specifically aromatic content) on smoke and flame radiation is examined experimentally under operating conditions typical of modern gas turbine combustors.

- Quigg, H.T., and Schirmer, R.M., "Effect of Vanadium on Hot Corrosion of Superalloys in Marine Environment," Phillips Petroleum Co. Research Division Report 4956-68R (Progress Report No. 3), 1968.

A screening program was conducted, using a high-pressure burner rig, to evaluate the effect of vanadium on hot corrosion of a turbine-blade alloy in a marine environment. Specimens of Inconel 713C were exposed for periods of up to 55 hours to exhaust gases from Phillips 2-Inch Combustor operated at 2000°F conditions with 0.40 weight per cent sulfur in a JP-5 fuel, 0.063 ppm vanadium in air, and zero and 1.0 ppm sea salt in air. The concentration of 0.063 ppm vanadium in air was equivalent to 3.8 ppm vanadium in fuel. Data from a previous investigation, in the absence of vanadium, were available and were used as the base line for the investigation.

Visual appearance, specimen weight-loss and metallographic examination of representative specimen were used in evaluating the effect of vanadium on hot corrosion. Metallographic examination showed evidence of vanadium attack by penetration of the surface layer of depleted alloy; so while weight-loss can be used for evaluating the extent of attack, it may underestimate the vanadium attack. The presence of 0.063 ppm vanadium in air increased weight-loss with both zero and 1.0 ppm sea salt in air, with the attack being more than doubled.

- Quigg, H.T., Schirmer, R.M., and Bagnetto, L., "Effect of Sulfur in JP-5 Fuel on Hot Corrosion of Turbine Blade Materials in Marine Environment," Phillips Petroleum Co. Research and Development Report 5903-71, 1971.

An experimental investigation is being conducted to determine the magnitude of the reduction in fuel sulfur required to improve the durability of turbine-blade materials in high-performance engines when operated in a marine environment. Previous studies by Phillips for the Navy have shown that little or no benefit would result from lowering the sulfur limit to 0.04 weight per cent, which approaches the medium of current production for JP-5; however, hot corrosion was decreased significantly for most materials tested by use of essentially sulfur-free fuel containing 0.0004 weight per cent. This study was made to establish whether that improvement in durability is associated with a "threshold" concentration of sulfur in fuel.

The work was done using Phillips Turbine Simulator operated at 15 atmospheres pressure with gas temperature and velocity at the test specimens cycled from 1000 to 2000°F and 163 to 275 ft/sec by control of

fuel flow. Sea water was added at a concentration equivalent to 1 ppm sea salt in the inlet air. Specimens of 13 different superalloys and 20 different superalloycoating systems were exposed from 5 to 165 hours using a fuel containing 0.0040 weight per cent sulfur, in an experiment designed to permit direct comparisons with previous tests using fuels containing 0.040 and 0.0004 weight per cent sulfur. The effect of sulfur concentration in fuel was evaluated by measurements of the weight and composition of surface scale on the specimens, visual and metallographic examination of the specimens, and measurement of metal weight-loss by the specimens.

It is concluded from these data that a 100-fold reduction in the present JP-5 sulfur limit to 0.004 weight per cent, which is near the minimum of current production, would not reduce hot corrosion significantly. There is evidence that the "threshold" concentration of sulfur in fuel for improved durability is related to sodium concentration; therefore, it is recommended that this investigation be extended to include other levels of sea salt ingestion.

A short-term test indicated that the addition of benzotriazole (100 ppm) to aviation-turbine fuel had little or no effect on hot corrosion; however, a more complete evaluation should be conducted.

- Quigg, H.T., "Effect of Prevaporized JP-5 Fuel on Combustor Performance," Final Report Naval Air Systems Command Contract N00019-71-C-0486, Phillips Petroleum Co. Res. and Dev. Report 6413-72, 1972.

An experimental investigation was conducted, using the Phillips 2-inch combustor operated under conditions simulating those in modern aircraft turbine engines, to determine effects of differences in JP fuels on flame radiance and exhaust emissions of nitrogen oxides, carbon monoxide, unburned hydrocarbon and soot. Kerosine-type fuels spanning the range in molecular structure (normal paraffins, isoparaffins, cycloparaffins, and aromatics) were evaluated. In initial studies the fuels were prevaporized to minimize effects of differences in their physical properties. Empirical equations were developed for each of the five responses with the response expressed as a function of combustor pressure, inlet-air temperature, inlet-air humidity and fuels. It was concluded from the data obtained that total radiant energy and smoke emissions decrease with an increase in fuel hydrogen content. A specification based upon a fundamental fuel property, such as hydrogen content, rather than a performance test, such as sooting tendency, offers advantages. Hydrogen content can be determined accurately by a variety of test methods, allowing selection of the best methods for research, process control, and product inspection from differing procedures and equipment. The basic guidance it provides to the petroleum chemist, with respect to the requirements of refinery processes for upgrading jet fuel burning quality, is not subject to misinterpretation.

- Reeves, D., "Flame Radiation in an Industrial Gas Turbine Combustion Chamber," U.D.C. No. 621.438.056:535.23, Memo No. M.285.

Radiation properties of the flame were measured in a large combustion chamber; flame temperatures were deduced and the experimental results are presented in tables and graphically. The observations were made, using four fuels, over a range of pressures, velocities and fuel/air ratios, at four positions along the flame.

Analysis of the results was approached by developing an expression for non-luminous emissivity in terms of the combustion variables and comparing the values so obtained with the observed total emissivities; the ratio of total emissivity to ideal non-luminous emissivity varied between 0.5 and 5. A general expression for total emissivity was thereby obtained but included a term, the luminous emission coefficient, which could not be correlated satisfactorily; its values are shown graphically for a range of combustion conditions.

- Roberts, R., Peduzzi, A., and Vitti, G.E., "Experimental Clean Combustor Program, Phase II, Alternate Fuels Addendum," NASA CR-134970. Pratt and Whitney Aircraft Division, United Technologies Corporation. July 1976.

An alternate Fuels investigation was conducted as an addendum to Phase II of the NASA Experimental Clean Combustor Program. The objective was to experimentally determine the impacts, if any, on exhaust emissions, performance, and durability characteristics of the Hybrid and Vorbix low-pollution combustor concepts when operated on test fuels which simulate composition and property changes which might result from future broadened aviation turbine fuel specifications or use of synthetically derived crude feedstocks. Liner temperature levels were insensitive to variations in aromatic content over the range of conditions investigated.

- Robson, K., "The Influence of Changing Fuel Specification on Combustor Performance and Emissions: A Review of Derby Test Experience," Rolls-Royce Aero Division Derby Report DP-353, March 1979.

There are warnings of increased metal temperatures for engines operating at intermediate pressures (particularly those older designs employing simple cooling). These are facing a risk of reduced life. Thermal paint testing may require the use of reference fuels.

- Schirmer, R.M., and Miller, E.C., "Radiation From Jet Combustor Flames," Presented before the Division of Gas and Fuel Chemistry, American Chemical Society, Urban, Illinois, Meeting, May 15 and 16, 1958.

Characteristics of the energy radiated from aircraft gas turbine type combustion processes were investigated using a laboratory scale combustor. Two paraffinic test fuels, normal heptane and isooctane, and two aromatic test fuels, benzene and toluene, were evaluated. Three different test conditions were selected having operating pressures of 40, 150, and 450 inches of mercury absolute. Infrared flame emission and absorption spectra, from 0.5 to 15 microns in wavelength were obtained at five different locations around the combustor. This was also done without combustion, and without fuel; to obtain fuel, and air, absorption spectra.

The average transverse emissivity of the infrared spectral region for non-luminous flames was approximately 0.03; but it increased with

increasing flame luminosity, to nearly one. The transverse emissivity of the flames increased with increasing combustor pressure. In general, flame emissivities of the aromatic fuels were higher than those of the paraffinic fuels. Energy transferred by radiation to combustor parts was an appreciable portion of the total energy released in luminous flames, varying from less than one per cent to greater than ten per cent.

- Schirmer, R.M., McReynolds, L.A., and Dailey, J.A., "Radiation from Flames in Gas Turbine Combustors," S.A.E. Transactions 68, 554, (1960).

The effect of monocyclic versus polycyclic aromatic components, in JP-5 fuels having the same ASTM Smoke Points, on total flame radiant energy was investigated. The performance of research combustors and a J79 aircraft gas turbine engine single combustor operated at low (atmospheric) pressure showed that variations in aromatic type or content within the present JP-5 specification have no significant effect on flame radiation.

The performance of research combustors and a J57 aircraft gas turbine engine single combustor operated at high (5-15 atm) pressure showed that polycyclic aromatic fuel blends burn with higher flame emissivities than monocyclic aromatic fuel blends of comparable ASTM Smoke Point. Radiant heating of metal parts was shown to be a function of their location in the combustor because quenched combustion products can effectively absorb flame radiation.

A characteristic relationship between total flame radiant energy from a J57 combustor and CRC Luminometer number was obtained with 12 test fuels covering a broad range in burning characteristics. Because of the excellent correlation between fuel ratings obtained with the ASTM Smoke Lamp and the CRC Luminometer, it seems desirable to consider the latter as an alternate for characterizing fuels beyond the limit of the present test method.

The use of low-luminosity fuels gave major reductions in liner temperatures in the J57 combustor. However, such fuels do not insure large reductions in heat transfer to metal parts, as shown by a reduction of only 40°F in the afterburner liner temperature of a J75 aircraft gas turbine engine obtained with "JP-150."

- Schirmer, R.M., "Specification of Jet Fuel Hydrogen Content for Control of Combustion Cleanliness," Progress Report No. 1, Navy BuWep Contract N600(19)-58219, Phillips Petroleum Co. Research Div. Report 3195-62R, Feature No. 6049, 1962.

A critical analysis has been made of current test methods, Smoke Point and Luminometer Number, for evaluation of the burning quality of hydrocarbon fuels for aircraft gas turbine engines. Unfortunately, the laminar flow diffusion flame of the wick lamp differs appreciably from the highly turbulent combustion process in an aircraft gas turbine engine. Differences in the mechanism of soot formation, as evidenced by the effect of hydrocarbon structure, are discussed in detail. This can result in undue emphasis being placed upon the attainment of a jet fuel quality, such as a very high Luminometer Number, from which no significant benefit in terms of performance or durability can reasonably be expected.

Measurements of the cleanliness of aircraft gas turbine combustion processes, liner temperature and flame radiation, show a linear correlation with hydrogen content of the fuel. The cleanest burning fuels are those that contain the most hydrogen. A two- to fourfold improvement in repeatability and fourfold improvement in reproducibility over current test methods should be feasible with hydrogen content. The use of hydrogen content for specification of jet fuel burning quality is recommended.

- Schirmer, R.M., and Quigg, H.T., "Effect of JP Fuel Composition on Flame Radiation and Hot Corrosion," Summary Report Bureau of Naval Weapons Contract NOW 64-0443-d, Phillips Petroleum Co. Res. Div. Report 4230-65R, Feature No. 6059, 1965.

In the flame radiation study, measurements were made of the total radiant energy from flames of 25 different fuels in a combustor operating at 22 different conditions. In general, flame radiation increased with increasing combustor pressure, inlet air temperature and heat input rate, and decreased with increasing flow velocity. However, the magnitude of these effects varied with both operating conditions and fuel composition. Relationships were established which showed flame radiation to decrease with increasing fuel hydrogen content and fuel Luminometer Number, at a given operating condition. Overall, the error in prediction of flame radiation from hydrogen content was about half that from Luminometer Number. It is concluded that the use of hydrogen content would be better than Luminometer Number for specification of JP fuel burning quality.

In the hot corrosion study, measurements were made of the metal lost by specimens of 6 different superalloys from exposure to 27 different simulated turbine blade environments. In general, corrosive attack increased with increasing gas temperature and "sea salt" concentration. However, the magnitude of these effects varied with both alloy composition and fuel sulfur content.

- Schirmer, R.M., and Quigg, H.T., "Effect of Very Low Sulfur in JP-5 Fuel on Hot Corrosion," Proceedings of the Tenth National Conference on Environmental Effects on Aircraft and Propulsion Systems, Trenton, New Jersey, May 1971.

During this investigation, it was found that the use of an essentially sulfur-free fuel, containing only 4 ppm sulfur, significantly decreased both the surface scale on specimens and the weight lost by specimens of a wide variety of superalloys and superalloy-coating systems when exposed under conditions which simulate those in an aircraft-turbine engine ingesting air with 1 ppm sea salt. Thus, indications are that the sulfur in fuel must be below a "threshold" concentration to improve the durability of turbine-blade materials, and we suspect that this "threshold" varies with the sodium concentration in the environment. Since modernization of petroleum refining processes to meet the demands for air pollution control presents an opportunity for achieving a major reduction in the sulfur content of aviation-turbine fuels, it is recommended that a service test be conducted to determine the magnitude of benefit which can be obtained by

use of an essentially sulfur-free fuel when operating in a marine environment.

An experimental investigation for the Naval Air Systems Command is in progress to determine whether the present limit of 0.4 per cent by weight (4,000 ppm) of sulfur in JP-5 fuel is a safe level for the protection of turbine-blade materials from hot corrosion in high-performance engines when operated in a marine environment. Past studies by Phillips have shown that little or no benefit would result from an order-of-magnitude reduction in the sulfur limit to 400 ppm. The present study shows that a 100-fold reduction in the sulfur limit to 40 ppm would not reduce hot corrosion significantly. Such reductions in the sulfur limit would drastically curtail fuel availability, since they approach the mean and the minimum of current production, and could cause critical problems in logistics. Therefore, no change in the sulfur limit for JP-5 to alleviate hot corrosion of turbine-blade materials is recommended at this time.

- Schirmer, R.M., "Effect of Fuel Composition on Particulate Emissions From Gas Turbine Engines," in Emissions from Continuous Combustion Systems, edited by W. Cornelius and W.G. Agnew, Plenum Publishing Corp., New York, 1972.

A critical analysis has been made of the test methods, Smoke Point and Luminometer Number, which are used at present to evaluate the burning quality of hydrocarbon fuels for gas turbine engines. Differences in the mechanism of soot formation, between a wick lamp and gas turbine combustor, as evidenced by the effect of hydrocarbon structure, are discussed in detail. Relevant information is reviewed on both the effect of smoke-abatement fuel additives and the morphology of particulate emissions. It is concluded that a specification based upon a fundamental fuel property, such as hydrogen content, rather than a performance test, such as sooting tendency, offers several advantages.

- Street, W.L., "Characteristics of Flame Radiation of High Temperature Hydrocarbon Fuels," Phillips Petroleum Co. Research Division Report 2307-59R, Feature No. 6024, April 1959.

Investigation of the effects of a monocyclic and several polycyclic hydroaromatic high temperature hydrocarbon fuels on flame radiation and flame tube metal durability has been conducted in a two-inch laboratory scale combustor under simulated conditions of sea-level takeoff, medium altitude cruising and high altitude loitering flight. Isoparaffinic and aromatic fuels were also included for reference purposes. Supplementary data obtained include deposition, smokiness, combustion efficiency, flame radiation in the Phillips Microburner and ASTM smoke point. Although differences intransverse flame radiation, flame tube metal temperatures and flame tube metal losses were observed among the five polycyclic hydroaromatic fuels tested, these appear significant only in the cases of isopropyl bicyclohexyl and dimethano decalin at simulated sea-level takeoff (high combustor pressure) where these two fuels tended to perform much like the aromatic reference fuels, causing high radiation fluxes and high metal loss rates.

Diethylcyclohexane, the single monocyclic hydroaromatic tested, exhibited relatively low radiation fluxes, flame tube metal temperatures and flame tube metal losses, making it appear comparable to the isoparaffinic reference fuels at all test conditions.

Measurements of flame radiation downstream from the combustor, intended to yield an indication of the amount of radiation incident upon downstream engine elements such as turbine stator and stream engine elements such as turbine stator blades, were somewhat difficult to interpret because of varying degrees of carbon particle survival. However, somewhat lower values were shown for the wide boiling range alkyl polycyclic fuel (HTF-36). This may very possibly have resulted from the lower combustion efficiency observed with this fuel. At any rate it would appear desirable in any future investigations, to provide means for actually measuring metal losses of downstream elements.

A correlation plot of flame tube metal losses versus transverse flame radiation showed this relationship to be mildly useful in predicting metal losses. However, it was found that flame tube metal temperature measurements did not accurately predict metal loss rates. In view of these results and the limited discrimination between fuels shown in the data obtained at the two lower severity conditions it would appear that in future work involving experimental fuels of limited availability, very nearly as much useful information (with a greatly reduced expenditure of fuel and time) might be provided by running metal loss tests at the more severe (sea-level takeoff) condition only, obtaining transverse flame radiation measurements while these runs are in progress.

Flame radiation tests conducted with the Phillips Microburner and ASTM Smoke Lamp tests have demonstrated the inability of these atmospheric pressure devices to adequately describe the flame radiation (and hence metal durability) performance of the test fuels in this program at high combustor pressures.

- Streets, W.L., "Gas Turbine and Jet Engine Fuels," Progress Report No. 5 Navy Contract NOas 6009-C, Phillips Petroleum Co. Res. Div. Report 2690-60R, 1960.

The flame tube durability tests with cyclic organo sulfur compounds added to low-sulfur base fuel have indicated that: (1) the time rate of metal loss increases with increases in sulfur concentration; (2) the slight differences observed between sulfur compounds fall within the repeatability band of the test method, indicating that these materials do not differ appreciably in their effect on flame tube durability and that gross sulfur concentration, rather than the form in which it exists, defines the degree of deterioration of flame tubes.

- Streets, W.L., "Gas Turbine and Jet Engine Fuels," Progress Report No. 2, Navy Contract NOas 60-6009-C, Phillips Petroleum Co. Res. Div. Report 2572-60R, 1960.

Results of the flame tube durability tests have indicated that: (1) the time rate of metal loss increases with increases in sulfur

concentration; (2) the slight differences observed between sulfur compounds fall within the repeatability band of the test method, indicating that these materials do not differ appreciably in their effect on flame tube durability and that sulfur concentration, rather than the form in which it exists, defines the degree of deterioration of flame tubes.

- Tretyachenko, G.N., Kosygin, E.P., and Kravchuk, L.V., "Effect of Sulfur Compounds Contained in Combustion Products of Fuels on the Failure of the Surface Layers of Turbine-Blade Materials", Strength of Materials, V.7 (10) July 1976.

A method of laminar spectral analysis and the results of study of the surface layer of turbine-blade materials tested both under their natural operating conditions, and in a wind tunnel under various cyclic temperature conditions were reported earlier. In the wind-tunnel studies, the chemical composition of the gaseous stream remained the same, since the same fuel - grade KO-25 illuminating kerosene conforming to GOST 4753-68 with 0.05% of S by weight - was used for the study.

In our study, turbine blades were tested under the action of a gaseous stream whose sulfur content increased and varied from scheme to scheme. In this case, the parameters of the temperature cycle were held constant and corresponded to scheme III (150 - 1250°C for the gas). Nozzle (alloy EP99) and rotor (alloy EI826) blades of naval gas-turbine engines have been studied.

The data obtained suggest a similarity between the processes of variation in the chemical composition of the surface layers and those described earlier. As is apparent, the molybdenum, iron, and tungsten contents in the surface layer increases, while the chromium, titanium, aluminum, and manganese concentrations diminish. Figure 1 shows the quantitative variation of the concentration of elements on the leading edge of blades with a loading history of 3000 cycles as a function of sulfur content in the stream.

A dimensionless coefficient equal to the ratio of the absolute value of the increase (decrease) in the concentration K to the concentration of the element of the unimpaired material K is adopted as a rating characteristic. The results of studies for the scheme with 0.05% of S after 2000 and 11,000 loading cycles are also presented here.

- Troth, D.L., "Low-Emissions Combustor Demonstration," USAAMRDL-TR-76-29, (DDA EDR 8723), March 1977.

The objectives of this eighteen-month program were to further develop two low-emission combustors - the prechamber combustor and the modified conventional combustor - which had previously demonstrated low emissions in USAAMRDL Contract DAAJ02-72-C-0005, to install them in a Detroit Diesel Allison Model 250-C20B engine, and to evaluate their performance in an engine environment. The combustors were to retain the 50% overall reduction in gas turbine mass emissions ($CO + CH_x + NO_x$) with no increase in any individual pollutant when tested over a typical Army light observation helicopter (LOH) duty cycle. The prechamber combustor was tested for

exhaust temperature profile, cyclic durability, and exhaust emissions on JP-4, JP-5, and an oil shale fuel refined toward a JP-5/Jet-A specification. The modified conventional combustor was engine tested to assess exhaust temperature profile and exhaust emissions from JP-4 fuel.

Both low-emission concepts demonstrated significant reductions in exhaust emissions when compared with the base-line combustor, although neither combustor completely met all of the emissions goals. Combustor exhaust temperature profile and liner durability were adequate, causing no engine damage or liner failures after more than 92 engine test hours covering the full range of engine operation.

- Vogel, R.E., Troth, D.L., and Verdouw, A.J., "Fuel Character Effects on Current, High Pressure Ratio, Can-Type Turbine Combustion Systems," Air Force Aero Propulsion Laboratory Report No. AFAPL-TR-79-2072, Feb. 1980.

The effect of limited fuel property variation on the performance of current, high pressure ratio can-type combustors was evaluated. The TF41 turbofan combustor was employed. This combustor has conventional dual-orifice fuel injection and film cooling. The combustion zone is approximately stoichiometric at takeoff. Twelve experimental fuels, including JP-4 and JP-8, were tested. Boiling range, hydrogen content, and aromatic type were varied by blending JP-4 and JP-8 fuel with mineral seal oil and two types of aromatic solvents. Fuel hydrogen content varied from 14.5% to 12%. Performance tests were accomplished at idle, altitude cruise, dash, and takeoff conditions. Sea level and altitude ignition tests were also completed. Fuel fouling and carboning characteristics were established. Combustor operating parameters such as liner temperature pattern factor, ignition fuel-air ratio, lean blowout fuel-air ratio and exhaust emissions were correlated to fuel properties. The effect of fuel properties on combustor and turbine hardware durability was assessed analytically.

SECTION II

Exhaust Smoke And Soot Formation

The effects of fuels on smoke formation are identical to those discussed in Section I for effects on radiation. Smoke suppressant additives work in two different ways - some reduce smoke by reducing soot formation, and hence radiation, while others have an effect only on the oxidation of soot after formation.

- Bagnetto, L., and Schirmer, R.M., "Smoke Abatement in Gas Turbines- Part I: Survey of Operating Variables," Phillips Petroleum Research Division Report 4884-67R, Jan 1968.

An experimental investigation was conducted to determine the effects of operating conditions and fuel composition on exhaust smoke and flame radiation. Phillips 2-inch combustor was used to simulate the conditions for combustion found in aircraft-turbine engines. These conditions were established by controlling combustor pressure, gas velocity, heat-input rate, and inlet-air temperature; and these parameters were varied independently to study their effect. The JP-5 type fuels were selected to represent a broad range in sooting tendency, and one was treated with a smoke-suppressant additive. This survey was used in the design of an experiment for Part II of this contract, which will evaluate the relative performance of three smoke-suppressant additives in aviation-turbine fuel.

In general, our observations indicate that to reduce smoke emissions from aircraft-turbine engines (a) combustors should be operated at minimum inlet-air temperature and pressure, with maximum exhaust-gas temperature; and (b) fuels should be selected for maximum hydrogen content. At operating conditions where high smoke densities were experienced with the untreated fuel, the smoke-suppressant additive was effective in reducing exhaust smoke. On the basis of these data, the Part II study under this contract will evaluate smoke-suppressant additives at combustor operating conditions covering a broad range of inlet-air temperature and pressure while maintaining gas velocity and heat-input rate at a constant and reasonable level. Also, these additives will be evaluated in several fuels, differing as widely as possible in hydrocarbon structure.

An exploratory study to determine the effect of the addition of 0.5 per cent by weight of "Freon" FE-1301 fire-suppressant agent to aviation-turbine fuel showed little or no change in combustion stability, combustion efficiency, flame-radiation intensity, and exhaust-smoke density.

An exploratory study to determine the effect of filter pore size when sampling exhaust-gas smoke showed little change using the AED smokemeter, with Millipore filters having pore size of 0.22, 0.45, 1.2, and 5 microns giving relative optical densities of 1.5, 1.3, 1.1, and 1.0. Also, a satisfactory correlation was found between AED and Von Brand smokemeters; both of which measure the "blackness" of soot filtered from the exhaust gas.

- Bagnetto, L., "Smoke Abatement in Gas Turbines - Part II: Effects of Fuels, Additives and Operating Conditions on Smoke Emissions and Flame Radiation," Phillips Petroleum Research Division Report 5127-68, ASTIA AD-842-818L September 1968.

An experimental program, using Phillips 2-inch combustor to simulate the conditions for combustion found in aircraft-turbine engines, was conducted to determine the effects and interactions of fuels, additive treatments, and operating conditions on aircraft-turbine smoke emission and flame-radiation characteristics. The test program included five base fuels, selected to span a broad range in aviation-turbine fuel hydrocarbon structure, three organometallic smoke-suppressant additives (Mn, Ba, Ca), and three concentration level of each additive. Each of the fuel-additive-concentration combinations were evaluated over a range of combustor inlet pressures of 7.5-15.0 atmospheres and combustor inlet-air temperatures of 400-1000°F, while maintaining gas velocity and the temperature rise in the combustor (about 1000°F) constant.

Analysis of the data was made by statistical procedures and the specific details and conclusions are provided. Projection of the results from mathematical relationships derived from the statistical analysis indicated the following trends: Fuel quality in terms of hydrogen content, fuel volatility and smoke-suppressant additive treatments will decrease in importance for controlling smoke emission as the severity of turbine-inlet conditions increase beyond 15 atmospheres and 1700°F. At 25 atmospheres and 2100°F the smoke emissions problems should vanish; however, a severe flame-radiation problem should be anticipated, regardless of fuel quality, fuel volatility or smoke-suppressant additives employed.

- Bagnetto, L., "Smoke Abatement in Gas Turbines - Part III: Effects of Smoke-Abatement Additives on Downstream Flame Radiation," Phillips Petroleum Research Division Report 5192-68, ASTIA AD-851-247L, Sept 1968.

An experimental program, using Phillips 2-inch combustor to simulate the conditions for combustion found in aircraft turbine engines, was conducted to determine the effects and interactions of smoke-suppressant additives and operating conditions on downstream flame-radiation intensity. The test program included a JP-5 base fuel, three organometallic smoke-suppressant additives (Mn, Ba, Ca,) and three concentrations of each additive (0.012, 0.024, and 0.036 g-atoms of metal per gallon of fuel). Each of the fuel-additive-concentration combinations were evaluated over a range of combustor inlet pressure of 7.5 - 15.0 atmospheres and combustor inlet-air temperature of 400 - 1000°F, while maintaining gas velocity and the temperature rise in the combustor constant.

The data indicate that soot in the exhaust gas acts as a screen to reduce downstream flame-radiation intensity. Since smoke-suppressant additives reduced the amount of soot in the exhaust gas, the JP-5 base fuel benefitted more from the screening effect; hence, fuels containing additives resulted in relatively higher downstream flame-radiation intensity. At conditions where soot in the exhaust gas was low, the use of Lubrizol 565 (Ba) and to lesser extent Lubrizol 239 (Ca) showed consistent

tendencies to reduce both transverse and axial (downstream) flame-radiation intensity below the performance of the base fuel, and indicates that alkaline-earth-type additives, to some degree, suppress flame radiation in primary combustion zone. Additive concentration over the range studied had little significant effect on flame-radiation characteristics and no definite trends were indicated.

- Bert, J.A., "Review of Early Aviation Turbine Engine Liner Temperatures and Exhaust Smoke Data," Unpublished Report dated December 20, 1978, circulated to CRC Panel.

Liner temperature and exhaust smoke data from a JT-3 combustor operated on 34 petroleum test fuels of varying aromatic (0.8 - 80.5%) and hydrogen (10.9 -15.8%) content were reevaluated. Liner temperature correlated significantly better with hydrogen content than with smoke point, luminometer number, SVI, or naphthalene content. Hydrogen content is recommended as the specification for control of liner temperature and smoke.

- Blazowski, W.S., Fahrenbruck, F.S., and Tackett, L.P., "Combustion Characteristics of Oil Shale Derived Jet Fuels," Paper 75-13, Western States Section/Combustion Institute, Oct 1975.

This paper reports on investigation of jet fuels derived from Colorado oil shale deposits. Combustor rig testing was performed on both as-received and clay treated fuels using a T56 single combustor scaled to examine a wide variety of engine types. Combustor liner temperatures for the case of the oil shale JP-4 were much the same as with petroleum JP-4. Similar results were found in the JP-5 testing. Increased smoke during testing of oil shale JP-5 was observed. Further comparative testing using oil shale and petroleum JP-4 fuels in an afterburning J85-5 turbojet engine showed no performance differences, although a slight NO increase was detected at idle operation.

- Blazowski, W.S., "The Impact of JP4/JP8 Conversion on Aircraft Engine Exhaust Emissions," AFAPL-TR-76-20, May 1976.

JP4 and JP8 were evaluated in a T56 single can combustor test rig and a J85-5 engine. Changes in emission characteristics were measured and are reported. Projections of the impact of JP4 to JP8 conversion on military aircraft emissions are made.

- Blazowski, W.S., "Combustion Considerations for Future Jet Fuels," Sixteenth (International) Combustion Symposium, Aug 1976, The Combustion Institute.

T56 combustor rig tests were performed with test fuels consisting of JP4/Xylene blends (12.7 to 14.5 percent hydrogen by weight), high fuel bound nitrogen blends, and two oil shale derived JP4 fuels. Liner temperature, exhaust emissions, and smoke were measured and correlated with fuel properties and combustor operating conditions. Smoke emission increased with decreased hydrogen content.

- Blazowski, W.S., and Jackson, T.A., "Evaluation of Future Jet Fuel Combustion Characteristics," AFAPL-TR-77-93, July 1978.

The impact of lower fuel hydrogen content on combustor liner temperatures, smoke, and gaseous emissions has been evaluated and improved correlations with hydrogen content have been developed. Results obtained with the various fuel blends tested have confirmed the dominant influence of hydrogen content on combustion characteristics when compared to volatility and hydrocarbon type effects. However, comparison with data obtained using low-smoke combustor design indicated that newer designs having airblast fuel injection and leaner combustion may be much less sensitive to fuel hydrogen content. The effectiveness of a smoke abatement fuel additive and a lean combustor primary zone have also been investigated. The additive reduced smoke emission but not liner temperature while the lean primary zone resulted in lower liner temperatures but no significant smoke emission decrease.

- Blazowski, W.S., Edelman, R.B., and Harsha, P.T., "Fundamental Characterization of Alternate Fuel Effects in Continuous Combustion Systems," Contract EC-77-C-03-1543, Sept. 1978.

The overall objective of this contract is to assist in the development of fuel-flexible combustion systems for gas turbines as well as Rankine and Stirling cycle engines. The primary emphasis of the program is on liquid hydrocarbons produced from non-petroleum resources. Fuel-flexible combustion systems will provide for more rapid transition of these alternate fuels into important future energy utilization centers (especially utility power generation with the combined cycle gas turbine). The specific technical objectives of the program are to develop an improved understanding of relationships between alternate fuel properties and continuous combustion system effects, and to provide analytical modeling/correlation capabilities to be used as design aids for development of fuel-tolerant combustion systems. Efforts this past year have been to evaluate experimental procedures for studying alternate fuel combustion effects and to determine current analytical capabilities for prediction of these effects. Jet Stirred Combustor studies during this period have produced new insights into soot formation in strongly backmixed systems and have provided much information for comparison with analytical predictions. The analytical effort included new applications of quasi-global modeling techniques as well as comparison of prediction with the experimental results generated.

- Blazowski, W.S., "Dependence of Soot Production on Fuel Blend Characteristics and Combustion Conditions," ASME Paper 79-GT-155, 1979.

Decreased fuel hydrogen content resulting from an increased aromatic content has been observed to result in increased exhaust smoke and particulates as well as greater flame luminosity. A small scale laboratory device which simulates the strongly back-mixed conditions present in the primary zone of a gas turbine combustor is utilized. Presented are incipient soot limits and soot production (mg/l) for a variety of fuels.

The influences of combustor inlet temperature and reactor mass loading have been evaluated and the sooting characteristics of fuel blends have been studied. These results have been analyzed to develop useful correlations which are in general agreement with existing mechanistic concepts of the soot formation process.

- Blazowski, W.S., Sarofim, A.F., and Keck, J.C., "The Interrelationship Between Soot and Fuel NO Control in Gas Turbine Combustors," ASME-80-GT-76, 1980.

The decreased hydrogen content of future fuels will lead to increased formation of soot, while increased organically bound nitrogen in the fuel can result in excessive NO emission. Control concepts for these two problems are in conflict: prevention of soot requires leaner operation while control of emissions from fuel nitrogen requires fuel-rich operation. However, recent results of two DOE research programs point to both processes having a major dependence on "hydrocarbon break-through." Control of both fuel nitrogen conversion and soot formation can be achieved by primary zone operation at equivalence ratios just below that for hydrocarbon breakthrough. This paper reviews the evidence for the importance of hydrocarbon breakthrough, explains our current understanding of why hydrocarbon breakthrough is important, and offers suggestions of how these results might be applied.

- Butze, H. F., and Ehlers, R. C., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor," NASA TM X-71789, October, 1975.

The performance of a single-can JT8D combustor was investigated with a number of fuels exhibiting wide variations in chemical composition and volatility. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons and NO_x, as well as liner temperatures and smoke. At the simulated idle condition no significant differences in performance were observed. At cruise, liner temperatures and smoke increased sharply with decreasing hydrogen content of the fuel. No significant differences were observed in the performance of an oil-shale derived JP-5 and a petroleum-based Jet A fuel except for emissions of NO_x which were higher with the oil-shale JP-5.

- Butze, H. F., and Liebert, C. H., "Effect of Ceramic Coating of JT8D Combustor Liner on Maximum Liner Temperatures and Other Combustor Performance Parameters," NASA TM X-73581, December, 1976.

The effect of ceramic coating of a JT8D combustor liner was investigated at simulated cruise and takeoff conditions with two fuels of widely different aromatic contents. Substantial decreases in maximum liner temperatures and flame radiation values were obtained with the ceramic-coated liner. Smaller reductions in exhaust-gas smoke concentrations were observed with the ceramic-coated liner. No deterioration of the ceramic coating was observed after about 6 hours of cyclic operation including several startups and shutdowns.

2 Butze, H. F., and Smith, A. L., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor at Simulated Idle, Cruise, and Takeoff Conditions," NASA TM-73780, September, 1977.

The performance of a single-can JT6D combustor was investigated with a number of fuels exhibiting wide variations in chemical composition and volatility. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons and NO, as well as liner temperatures and smoke. The most pronounced effects of changes in fuel composition were observed at simulated cruise and takeoff conditions where smoke and liner temperatures increased significantly as the hydrogen content of the fuel decreased.

- Butze, H.F., and Humenik, F.M., "Parametric Performance of a Turbojet Engine Combustor Using Jet A and a Diesel Fuel," NASA-TM-79089, March, 1979.

The performance of a single-can JT8D combustor was evaluated with Jet A and a high-aromatic diesel fuel over a parametric range of combustor-inlet conditions. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons, and NOx, as well as liner temperatures and smoke. At all conditions the use of diesel fuel instead of Jet A resulted in increases in smoke numbers and liner temperatures; gaseous emissions, on the other hand, did not differ significantly between the two fuels.

- Carl, D.E., Obidinski, E.S., and Jersey, C.A., "Exhaust Emissions from a 25-MW Gas Turbine Firing Heavy and Light Distillate Fuel Oils and Natural Gas," ASME Paper No. 75-GT-68, March 2-6, 1975.

Heavy and light distillate fuel oils and natural gas were compared during this emissions test. As expected, the emissions using natural gas were normally much less than with No. 2 oil. The noteworthy differences of this test relate to the two distillate oils. There were no significant differences between the emission levels of NOx, CO, or unburned hydrocarbons for the two. Using the heavy distillate oil, there were higher SO₂ emissions (which is in agreement with the fuel sulfur levels), lower smoke levels, and higher particulate levels than with No. 2 oil.

2 Clark, J.A., et al., "Radiation/Smoke and Combustion Efficiency from Gas Turbine Flames, IV., Fuel Property Effects on Performance," PURDU-CL-79-05, March 1979. (USATARADCOM DAAE07-76-C-0063, Technical Report No. 12438).

The performance of gas turbine combustors with respect to combustion efficiency, flame stabilization, ignition, smoke and radiation, burning a wide range of fuel types is considered. The experimental portion of the program was conducted with a simplified combustor designed to yield apparatus independent results. Experimental results are provided for radiation and smoke measurements. These results include radiation intensity and emissivity measurements from two fuels, smoke mass concentrations and particle size measurements at various locations inside the combustor. Theoretical calculations based on the smoke data significantly underpredict the actual flame radiation.

- Clarke, A.E., Hunter, T.C., and Gardner, F.A., "The Tendency to Smoke of Organic Substances on Burning," Part I., J. Inst. Petr. 32, 627, (1946).

A burning organic substance has a flame-height at, and above which, smoking occurs, and this height is a measure of the tendency to smoke. A new form of lamp was devised to measure flame-heights, from about 9 to 450 mm, of liquid compounds burning freely in air. A wide range of hydrocarbons, alcohols, ketones, esters, and nitro-compounds was examined - 115 compounds in all. In general, a compact molecule was found to give a smoky flame. The order for increasing tendency to smoke for hydrocarbons is: n-paraffins (in which increased chain length or chain branching gave increased smoke), naphthenes, olefines, and aromatics (in which appreciable aliphatic side chains on the benzene ring appeared to give no marked reduction in smoke). In general, increased oxygen content of an organic compound resulted in decreased smoking tendency and compounds, such as methyl acetate, containing high percentages of oxygen only smoked at very large flame-heights. Some compounds, such as allyl alcohol, although having appreciable oxygen contents, had relatively high smoking tendencies, due to the nature of the carbon-hydrogen portion of the compound. Of the aliphatic alcohols, the tertiary compounds were more smoky than the primary compounds. This also applied to nitro-paraffins. For each set of isomeric aliphatic esters, the flame-height at which smoking began increased with the chain length attached directly to the carboxylic carbon atom. At equal oxygen content, the general order for increasing tendency to smoke was: n-primary alcohols, n-primary nitro-paraffins, propionates, acetates, lactates, and formates, although the order varied slightly for different oxygen contents.

- Colket, M.B., Stefucza, J.M., Peters, J.E., and Mellor, A.M., "Radiation and Smoke from Gas Turbine Flames, Part II: Fuel Effects on Performance," PURDU-CL-77-01, 1977, (USATACOM DAAE07-76-C-0063).

Fuel effects upon gas turbine combustor performance, including combustion efficiency, lean blow off, smoke, and flame radiation, must be defined to minimize developmental efforts in adapting existing Army engines to synthetic and alternate fuels. Limited results for efficiency, blow off, and smoke concentrations are presented for a simulated combustor primary zone burning various fuels.

- Detroit Diesel Allison, "Model 501-K17 Gas Turbine Single Burner Evaluation of Shale Derived Marine Diesel Fuel," DDA EDR 8660, January 1976.

A significant quantity of crude oil has been extracted from Colorado oil shale in the Paraho project. This crude was subsequently experimentally refined to produce a broad range of military fuels. This report presents results obtained in gas turbine combustion tests of a marine diesel fuel from this project. A can-annular segment of the DDA 501-K17 marine gas turbine engine was used in the tests. Burner conditions simulated the operating spectrum experienced by this engine in the U.S. Navy DD963 class destroyers. Starting and steady state points from zero to

full power were examined. The performance of the shale fuel was compared with that obtained at equivalent conditions with a petroleum marine diesel fuel from the U.S. Navy supplies. Exhaust smoke was measurably higher with the shale fuel, but deemed no greater than possible with a minimum quality petroleum fuel to the same specification.

- Dodds, W.J., Colket, M.B., and Mellor, A.M., "Radiation and Smoke from Gas Turbine Flames, Part I: Carbon Particulate Measurements Within a Model Turbine Combustor," PURDU-CL-76-06, July 1976. (USATACOM DD4E07-C-0063).

Recent investigations of the combustion characteristics of coal and oil shale derived liquid fuels in gas turbine combustors (Hardin, 1974; Blazowski et al., 1975) have revealed that due to higher aromatic content the use of these fuels leads to significantly higher particulate levels than are encountered with comparable petroleum based fuels. This increase is objectionable from the standpoint of smoke emissions and may also be expected to increase radiative heat transfer to combustor walls, leading to possible engine damage. In an effort to quantify these problems and to identify reasonable combustor modifications and fuel specifications required for smoke-free operation, a program of carbon particulate measurement as a function of fuel type has been initiated. Based on a review of previous experimentation on gas turbine smoke formation, the form for a characteristic time model of smoke formation is suggested. The measurement system and model combustor to be used to obtain particle size and concentration data required for development and verification of the model are described. System tests are reported which indicate that errors due to anisokinetic sampling and particle deposition are negligible. Three similar jet fuels, including one derived from an oil shale, were burned in the test combustor. Axial concentration profiles for the centerline of the test combustor for each of these fuels are compared, showing increased particulate concentrations with increasing fuel aromatic content (by percent volume). Micrographs and particle size distributions obtained for oil shale and petroleum derived fuels show no conclusive evidence of changes in particle size as function of fuel origin. Based on the results of these tests, it has been concluded that the measurement system used is adequate for use in the development of the smoke formation model.

- Dodds, W.J., Peters, J.E., Colket, M.B., and Mellor, A.M., "Preliminary study of smoke found in the combustion of various jet fuels," J. Energy, 1, 115, (1977).

A simplified, disk-stabilized combustor has been used to study particulate sampling methodology and fuel effects on combustion zone particulate concentration. Five fuels - petroleum-based Jet A, low-aromatic Jet A, Jet A blended with 15 percent rubelene, petroleum based JP-4, and JP-5 refined from an oil shale derived syncrude - were investigated. Axial concentration profiles suggest a particulate emission dependence on fuel hydrogen (or aromatic) content as well as volatility. Measured primary zone particulate concentrations were two orders of magnitude greater than exhaust values.

- Ekstedt, E.E., and Macaulay, R.W., "Combustion of Heavy Distillate Fuel for the LM2500 Gas Turbine," ASME 72-GT-24, January 1973.

The combustor for the LM2500 is an annular combustor developed for use with marine and industrial fuels including natural gas and heavy distillates. This paper relates the development of this combustor including some of the design criteria, the fuel properties and some of the combustor performance results such as exit gas temperature patterns, ignition, pressure loss, and efficiency. The engine combustor operates with a clear smokeless stack utilizing heavy distillate fuels and is free of carbon formation. Fuel properties and atomization properties are related to exhaust smoke. Investigations have included a wide range of fuels and several fuel injector designs. The engine has operated in GTS Adm. Wm. M. Callaghan for a total of more than 10,000 hrs with no combustor problems, smoke, carbon, life or otherwise.

- Friswell, N.J., "The Influence of Fuel Composition on Smoke Emission from Gas-Turbine-Type Combustors: Effect of Combustor Design and Operating Conditions," Combustion Science and Technology, 19, 119 (1979).

The influence of fuel composition on smoke emission/combustor wall temperatures has been studied in a laboratory-scale gas-turbine-type combustor over the range of operating conditions of modern turbine combustors and as a function of combustor design. Fuel hydrogen content is shown to give the best prediction of smoke emission and of variations in flame tube wall temperature caused by changes in flame radiation. The major finding is that the influence of fuel composition on smoke emission/flame radiation falls virtually to zero at combustor pressures above about 10 bar. Significant reduction in sensitivity to fuel composition can also be obtained by varying combustor design and are tentatively correlated with increasing combustion intensity. The implication of these effects for aircraft operation is discussed and an explanation for the results is put forward based on changes in the chemical mechanisms leading to soot formation.

- Gleason C. C., and Bahr, D. W., "Alternate Fuels Addendum, Phase II. Experimental Clean Combustor Program." NASA CR-134972, January 1976.

A study was conducted to investigate the characteristics of current and advanced low-emissions combustors when operated with special test fuels simulating broader ranges of combustion properties of petroleum or coal-derived fuels. Five fuels were evaluated; conventional JP-5, conventional No. 2 Diesel, two different blends of Jet A and commercial aromatic mixtures - "xylene bottoms" and "naphthalene charge stock", and a fuel derived from shale oil crude which was refined to Jet A specifications. Three CF6-50 engine size combustor types were evaluated in a full annular combustor rig. For the five fuels tested, effects were generally quite moderate, but well defined. CO, HC, NO_x and smoke emissions levels and peak liner metal temperatures increased with decreasing hydrogen content of the fuel which ranged from 12.2 to 13.7 percent by weight. CO, HC and smoke emissions levels also increased with final boiling point of the fuel which ranged from 529 to 607°K. Effects on other characteristics were quite small.

- Gleason, C.C., and Eahr, D.W., "Experimental Clean Combustor Program: Diesel No. 2 Fuel Addendum, Phase 3," NASA-CR-135413, May 1979.

A CF6-50 engine equipped with an advanced, low emission, double annular combustor was operated 4.8 hours with No. 2 diesel fuel. Fourteen steady-state operating conditions ranging from idle to full power were investigated. Engine/combustor performance and exhaust emissions were obtained and compared to JP-5 fueled test results. With one exception, fuel effects were very small and in agreement with previously obtained combustor test rig results. At high power operating conditions, the two fuels produced virtually the same peak metal temperatures and exhaust emission levels. At low power operating conditions, where only the pilot stage was fueled, smoke levels tended to be significantly higher with No. 2 diesel fuel.

- Gleason, C.C., et.al., "Evaluation of Fuel Character Effects on the J79 Engine Combustion System," AFAPL-TR-79-2015, June 1979.

Results of a program to determine the effects of broad variations in fuel properties on the performance, emissions, and durability of the J79-17A turbojet engine combustion system are presented. Combustor tests conducted at engine idle, takeoff, subsonic cruise, supersonic dash, cold day ground start, and altitude relight operating conditions with 13 different fuels are described. The test fuels covered a range of hydrogen contents (12.0 to 14.5 percent), aromatic type (monocyclic and bicyclic), initial boiling point (285 to 393 K), final boiling point (552 to 679 K) and viscosity (0.83 to 3.25 mm²/s at 300 K).

At high power operating conditions, fuel hydrogen content was found to be a very significant fuel property with respect to liner temperature, flame radiation, smoke, and NO_x emission levels.

- Gleason, C.C., et al, "Evaluation of Fuel Character Effects on F101 Engine Combustion System, Final Report," AFAPL-TR-79-2018, June 1978.

Results of a program to determine the effects of broad variations in fuel properties on the performance, emissions and durability of the General Electric F101 augmented turbofan engine main combustion system are presented. Combustor rig tests conducted at engine idle, takeoff, cruise, dash, cold day ground start and altitude relight operating conditions with 13 different fuels are described. Fuel nozzle fouling tests conducted with the same fuels are also described. The test fuels covered a range of hydrogen contents (12.0 to 14.5%), aromatic type (monocyclic and bicyclic), initial boiling point (285 to 393 K), final boiling point (552 to 679 K) and viscosity (0.83 to 3.25 mm²/s at 300 K).

- Gleason, C.C., and Martone, J.A., "Fuel Character Effects on J79 and F101 Engine Combustion Emissions," ASME 80-GT-70, 1980.

Results of a program to determine the effects of fuel properties on the pollutant emissions of two US Air Force aircraft gas turbine engines are presented. Thirteen test fuels, including baseline JP-4 and JP-8, were

evaluated in a cannular (J79) and a full annular (F101) combustor. The principal fuel variables were hydrogen content, aromatic structure, volatility, and distillation end point. Data analysis shows that fuel hydrogen content is a key fuel property, particular with respect to high power emissions (oxides of nitrogen and smoke), and that low power emissions (carbon monoxide and hydrocarbons) are more dependent on fuel atomization and evaporation characteristics.

- Hardin, M.C., "Evaluation of Three Coal Derived Liquid Fuels in a Standard T63 Combustor," Detroit Diesel Allison Report RN74-28, Nov. 1974.

The combustion performance of three coal derived fuels was examined in a standard gas turbine engine combustor. The fuels were crude materials of varying volatility levels produced by FMC Corporation's COED process. Compared to aircraft petroleum derived fuels, exhaust smoking increased sharply as was anticipated from their higher aromatic contents.

- Hardin, M.C., and Stettler, R.J., "Initial Evaluation of Coal Derived Liquid Fuels in a Low Emission Turbine Combustor," General Motors Report, Engineering Publication A-3161, Sept. 1974.

A low emission combustor was tested with liquid coal fuels at a regenerative automotive gas turbine operating condition. Combustor performance was measured on three liquid coal fuels from the COED (char-oil-energy-development) process. The three fuels were a UTAH light fraction, a blend of 20% UTAH light and 80% heavy simulating a full range product and a topped full range product of Illinois #6 coal. The low emission combustor was operated in both a low emission mode and a mode simulating the conventional turbine combustor. Combustion efficiency under all conditions was above 99.5% and smoke was below the visible limit.

- Hoult, D.P., "Soot Formation in a Turbulent Swirling Flow," NASA CP 2021, M.I.T.; Aircraft Engine Emissions, A conference held at Lewis Research Center, May 18-19, 1977. p. 309-321.

The qualitative understanding of soot formation in simple models of gas turbine primary-zone combustors is summarized. Soot formation in flame radiation and air pollution was investigated. Results are presented, namely: (1) if the fuel is premixed with air in approximately stoichiometric proportions, the sequence of states that a fluid element undergoes as it burns is quite different from the sequence when liquid or vapor fuel is injected into an air-flow; (2) swirling flows, as are typical of swirl-can combustors, when burning, can amplify small aerodynamic disturbances upstream of the swirl vanes; and (3) different fuels form significantly different amounts of soot. Each of these effects makes major changes in the amount of soot formed in a given combustor.

- Ingebo, R.D., and Norgren, C.T., "Combustor Exhaust Emissions with Air-Atomizing Splash-Groove Fuel Injectors Burning Jet A and Diesel Number 2 Fuel," NASA TMX-3255, July 1975.

Air-atomizing splash-groove injectors, utilizing fuel jets impinging against a grooved face, gave improved primary-zone fuel spreading and

reduced combustor exhaust emissions for Jet A and diesel number 2 fuels. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air pressures of 41 to 203 N/cm², inlet-air temperatures of 477 to 811 K, and a reference velocity of 21.3 m/sec. With Jet A fuel, large-orifice splash-groove injectors reduced the oxides of nitrogen emission index to 15, a value 25 percent less than that for previously tested air-atomizing splash-cone nozzles, but did not reduce emissions of carbon monoxide, unburned hydrocarbons, or smoke (at 700 K, 203 N/cm², and an 0.018 fuel-air ratio). Small-orifice splash-groove injectors did not reduce oxides of nitrogen but reduced the smoke number to 11, or by 45 percent (at 700 K, 101 N/cm², and an 0.018 fuel-air ratio) and reduced carbon monoxide and unburned hydrocarbon emission indices to 35 and 12, or by 20 and 30 percent, respectively (at 477 K, 41 N/cm², and an 0.008 fuel-air ratio). With diesel number 2 fuel, the small-orifice splash-groove injectors (compared with pressure-atomizing nozzles) reduced oxides of nitrogen by 19 percent, smoke number by 28 percent, carbon monoxide by 75 percent, and unburned hydrocarbons by 50 percent. Smoke number and unburned hydrocarbons were twice as high with diesel number 2 as with Jet A fuel.

4 Ingebo, R.D., and Norgren, C.T., "Combustor Exhaust Emissions and Blowout Limits with Diesel Number 2 and Jet A Fuels Utilizing Air-Atomizing and Pressure Atomizing Nozzles," NASA-TM-X-71803; E-8483 (1975). Presented at Western States Section of the Combustion Institute, Palo Alto, Calif., Oct. 1975.

Experimental tests with diesel number 2 and Jet A fuels were conducted in a combustor segment to obtain comparative data on exhaust emissions and blowout limits. An air-atomizing nozzle was used to inject the fuels. Tests were also made with diesel number 2 fuel using a pressure-atomizing nozzle to determine the effectiveness of the air-atomizing nozzle in reducing exhaust emissions. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air total pressures and temperatures of 41 to 203 newtons per square centimeter and 477 to 811 K, respectively, and a reference velocity of 21.3 meters per second. Smoke number and unburned hydrocarbons were twice as high with diesel number 2 as with Jet A fuel. This was attributed to diesel number 2 having a higher concentration of aromatics and lower volatility than Jet A fuel. Oxides of nitrogen, carbon monoxide, and blowout limits were approximately the same for the two fuels. The air-atomizing nozzle, as compared with the pressure-atomizing nozzle, reduced oxides of nitrogen by 20 percent, smoke number by 30 percent, carbon monoxide by 70 percent, and unburned hydrocarbons by 50 percent when used with diesel number 2 fuel.

4 Lefebvre, A.H., and Durrent, T., "Design Characteristics Affecting Gas Turbine Combustion Performance," SAE 240C, Oct. 1960.

Fuel injector design and the distribution of fuel and air throughout the combustion zone can be the best cure for exhaust smoke from aircraft gas turbines. The importance of fuel type can thus be minimized. Evidence obtained from combustion rig tests and on actual engines has confirmed the

advantages claimed for the lighter kerosenes in terms of reduced smoke, easier ignition and higher combustion efficiency at extreme altitudes. These advantages could be very real on engines whose performance is limited by inadequate atomization of the fuel. However, the best cure for smoke lies in the design of the flame tube and fuel injector. Of particular importance is the primary zone fuel/air ratio which should be maintained as far as possible at or near the stoichiometric value. In this way not only is the level of exhaust smoke appreciably reduced, as compared with over-rich primary zone, but the sensitivity of liner temperature to fuel type is also very much less.

- Lefebvre, A.H., Mellor, A.M. and Peters, J.E., "Ignition/Stabilization/Atomization: Alternative Fuels in Gas Turbine Combustors," Progress in Astronautics and Aeronautics, 62, 137 (1978).

Certain aspects of gas turbine performance, namely, spark ignition, lean blowoff, and spray atomization, are considered in terms of the properties of conventional and alternative fuels. Those properties are identified which appear most relevant to performance both in practical combustors and laboratory simulations. For atomization the viscosity, surface tension, and density are important, whereas for spark ignition and flame stabilization both viscosity and distillation characteristics are significant. Past research in the latter two areas tends to be apparatus specific, although some qualitative trends can be identified. A combined property that characterizes the fuel spray, rather than either the fuel or the injector, is discussed. It is found that the evaporation time for the Sauter mean diameter of the spray appears to include all of the physical properties of the fuel which are important to atomization, lean blowoff, and spark ignition, and the criterion for the ignition and blowoff limits may be expressed adequately in terms of the maximum allowable mean droplet lifetime. The relevance of a characteristic droplet evaporation time to soot formation and combustion inefficiency also is discussed. Experiments and modeling to minimize combustor development for nonspecification fuels are suggested.

- Linden, L.H., and Heywood, J.B., "Smoke Emission from Jet Engines," Combustion Science and Technology, 2, 401 (1971).

The fundamental processes determining the amount of smoke in the exhaust of a gas turbine engine are examined. First, the configuration of modern combustors and the state of knowledge of the processes occurring within the combustor are reviewed. Data from laboratory flame studies of carbon formation are then discussed and correlated with engine and combustor exhaust studies. It is seen that solid carbon is the nonequilibrium product of fuel vapor-air combustion in locally fuel rich zones. Calculations of carbon oxidation rates are then used to show that significant fractions of the carbon formed in the rich regions of the primary zone may be consumed in the leaner regions of the primary zone and in the secondary zone. Finally, combustor design features desirable for minimal exhaust smoke are summarized, and areas where further research would be most beneficial are identified.

- Lipfert, F.W., "Impact of Alternate Fuels on Stationary Gas Turbine Operations and Siting," ASME Paper 74-GT-154, 1974.

An analysis of gas turbine ambient air quality impact is presented, from the standpoint of the acceptability of alternate fuels having higher sulfur content and possibly higher particulate emissions. Various plume rise formulas are compared, and formulas are given for maximum ground level concentrations for both short term (1 to 3 hr) and intermediate (3 to 24 hr) periods. The results show that the U.S. Federal Air quality standards may allow large gas turbine complexes (500 MW) burning up to 1% sulfur fuel, for example. Taking advantage of this capability could increase the supply of lower sulfur fuels for home heating and/or transportation use.

- Lohmann, R.P., Szetela, E.J., and Vranos, A., "Analytical Evaluation of the Impact of Broad Specification Fuels on High Bypass Turbofan Engine Combustors," NASA CR-159454, PWA 5565-15, Dec. 1978.

The impact of the use of broad specification fuels on the design, performance, durability, emissions and operational characteristics of combustors for commercial aircraft gas turbine engines was assessed. Single stage, vortex and lean premixed prevaporized combustors, in the JT9D and an advanced energy efficient engine cycle were evaluated when operating on Jet A and ERBS (Experimental Referee Broad Specification) fuels. Design modifications, based on criteria evolved from a literature survey, were introduced and their effectiveness at offsetting projected deficiencies resulting from the use of ERBS was estimated. The results indicate that the use of a broad specification fuel such as ERBS, will necessitate significant technology improvements and redesign if deteriorated performance, durability and emissions are to be avoided. Higher radiant heat loads are projected to seriously compromise liner life while the reduced thermal stability of ERBS will require revisions to the engine-airframe fuel system to reduce the thermal stress on the fuel. Smoke and emissions output are projected to increase with the use of broad specification fuels. While the basic geometry of the single stage and vortex combustors are compatible with the use of ERBS, extensive redesign of the front end of the lean premixed prevaporized burner will be required to achieve satisfactory operation and optimum emissions.

- Longwell, J.P., "Synthetic Fuels and Combustion," Prog. Energy Combust Sci, p. 127-138, 1977.

The term synthetic is used here to define fossil fuels manufactured from sources other than petroleum. As the supply of hydrocarbons for transportation fuels includes an increasing proportion of low hydrogen-to-carbon ratio sources, such as coal, the cost and waste of energy in converting these materials to the high hydrogen-to-carbon ratio fuels now required by land and air propulsion systems will increase. The main combustion problem is the increasing difficulty of avoiding the emission of soot. In automotive systems, the combustion problems appear much more easily solved for the stirling cycle and the gas turbine because of the steady flow conditions and the potentially longer time that can be provided for soot burnout.

- Marchionna, N.R., et al., "Turbine Fuel Tolerance Study, Initial Engine Test: No. 4 Oil," USATARADCOM Technical Report No. 12272, April 1977.

An AGT 1500 vehicular gas turbine engine was operated on No. 4 residual oil using a specially modified combustor. Smoke emissions were below the visible limit. There was no effect of the fuel on engine or recuperator performance.

- Marchionna, N., "Turbine Fuel Tolerance Study: Multifuel Engine Tests," USATARADCOM Technical Report 12392 (USATARADCOM DAAE07-74-C-0274) July 1978.

An AGT 1500 vehicular gas turbine engine was tested for multifuel capability. Overall performance did not vary when operating on JP-4, DF-2, or unleaded gasoline. Smoke and combustor liner wall temperatures were highest with gasoline and lowest with JP-4. These effects are attributed to a more luminous flame as a result of higher aromatic content in the gasoline.

- Martel, C.R., and Angello, L.C., "Hydrogen Content as a Measure of the Combustion Performance of Hydrocarbon Fuels," AFAPL-TR-72-103, May 1973.

Results of statistical correlations of fuel data are presented wherein the hydrogen content of fuels is correlated with other fuel combustion measurements including smoke point, luminometer number, and net heat of combustion. Results indicate that for a certain range of fuels knowing a fuel's hydrogen content eliminates the need to evaluate its smoke point, luminometer number, or its net heat of combustion.

- Moses, C.A., and Naegeli, D.W., "Effects of High Availability Fuels on Combustor Properties," AFLRL Report No. 101, AD-A054229, Jan. 1978.

A high pressure and temperature research combustor was operated over a matrix of conditions involving

- (a) burner inlet pressure, BIP = 2, 5, 10 and 15 atm,
- (b) burner inlet temperature, BIT = 532, 812 and 1034°K,
- (c) fuel/air ratio (heat input rate), H = 212, 424 and 848 KJ/Kg of air, and
- (d) reference velocity (turbulence and residence time), V = 22, 44 and 66 M/sec.

Six petroleum base JP-5 fuels (principally aromatic blends) and three JP-5 syncrudes (from oil shale, coal and tar sands) were examined.

Flame radiation and exhaust smoke from petroleum based fuels correlated equally well with fuel hydrogen, aromatics and ring carbon. The radiation and smoke from the syncrude fuels correlated best with hydrogen content. The oil shale and tar sand derived fuels behaved similarly to petroleum base fuels while the syncrude from coal gave relatively higher radiation and smoke based on its hydrogen content. Flame radiation and exhaust smoke were relatively insensitive to fuel at low levels of radiation and smoke, but at higher levels, the fuel sensitivity increased significantly.

- Moses, C.A., and Naegeli, D.W., "Fuel Property Effects on Combustor Performance," ASME Paper 79-GT-178, March 1979.

Two combustor rigs have been used to study the sensitivity of combustor performance to the physical and chemical properties of fuels. The purpose was to determine the impact of broadening fuel specifications and using non-specification fuels in emergencies. Nineteen fuels including synfuels were used to accentuate the properties of concern: composition, viscosity, and boiling point distribution. The combustors were instrumented for flame radiation, liner temperature, and exhaust emissions; testing included ignition, stability, and combustion efficiency.

Hydrogen content was the most effective correlating parameter for radiation and smoke; sensitivities to hydrocarbon structure were secondary. The syncrude fuels correlated the same way as the petroleum fuels. Higher end points did not affect the correlation, indicating the soot formation was due to gas-phase reactions not liquid-phase pyrolysis. Results indicate clean-burning combustors should have low sensitivity to hydrogen content.

- Naegeli, D.W., and Moses, C.A., "Effects of Fuel Properties on Soot Formation in Turbine Combustion," SAE Paper No. 781026, Nov. 1978.

A T-63 combustor rig has been used to study the sensitivity of combustor performance to the physical and chemical properties of fuels. The purpose was to determine the impact of broadening fuel specifications and using non-specification fuels in emergencies. The fuel properties of special concern were the composition, the distillation curve and viscosity. The first property is associated with the chemistry of carbon formation while the latter two are related to mixing as they affect the atomization and vaporization. The combustor was instrumented for flame radiation, exhaust smoke, and gaseous emissions. Measurements of these items were made at the full power condition. The hydrogen/carbon ratio was the most effective correlating parameter for radiation and smoke; sensitivities to molecular structure appeared to be secondary. Similar to the syncrude fuels, the water/fuel emulsions and methanol/aromatic blends correlated in the same way as petroleum fuels. Higher end points did not affect the correlation indicating that soot formation was due to gas phase reactions, not liquid phase pyrolysis. The results favor a chemical mechanism for the role of water in reducing soot.

- Naegeli, D.W., and Moses, C.A., "Effect of Fuel Molecular Structure and Soot Formation in Gas Turbine Engines," ASME Paper 80-GT-62, March 1980.

A high-pressure research combustor operating over a wide range of burner inlet conditions was used to determine the effects of fuel molecular structure on soot formation. Six test fuels with equal hydrogen content (12.8%) were blended to stress different molecular components and final boiling points. The fuels containing high concentrations (20%) of polycyclic aromatics and partially saturated polycyclic structures such as tetralin, produced more soot than would be expected from a hydrogen content

correlation for typical petroleum based fuels. However, fuels containing naphthenes such as decalin agreed with the hydrogen content correlation. The contribution of polycyclic aromatics to soot formation was equivalent to a reduction in fuel hydrogen content of about one percent. The fuel sensitivity to soot formation due to the polycyclic aromatic contribution decreased as burner inlet pressure and fuel/air ratio increased.

4 Nardi, G., "Low Emission Fuels and Devices for Aviation Engines," AGARD-CP-84-71, 1971.

A comparative test was performed on a jet engine combustor of the smoking characteristics of two types of fuel, type JP-5 and type A-1. The smoke concentration from the JP-5 tests was about 2.3 times that from the A-1. Data are also presented for smoke reduction by additives.

4 Opdyke, G., "The Effect of a Sample Lot of Fuel Injectors on Emissions Levels of a Small Gas Turbine," ASME Paper presented at the ASME 24th International Gas Turbine Conference, 11-15 March 1979 San Diego, ASME Paper 79-GT-165.

A single small gas turbine engine, containing an annular combustor producing nearly conventional emission levels, was sampled for gaseous emissions and smoke a total of 20 times in a one month period. Five samples each of two fuel injector designs were tested in random order, and the combustor angular orientation was varied with respect to the compressor. In addition to the basic tests with aviation kerosene fuel, emission measurements were also made with Avgas and diesel fuel with each injector design. Fuel spray drop size distributions were estimated from sample test data. The result of changing the fuel injectors was the production of a significant variation in hydrocarbon and carbon monoxide emissions, with limited variation in oxides of nitrogen and smoke. After correction for ambient and operating conditions, the standard deviation in the EPA parameter for hydrocarbons was about 30% of the average value and 15% of the average value for carbon monoxide. It was postulated that the variation was caused by fuel injector manufacturing tolerances which resulted in large variations in the maximum drop size in individual sprays causing variable entrainment of unvaporized drops in the wall cooling film. The conclusion is that small, and perhaps non-detectable, variations in injectors can cause changes in emissions from gas turbines, and, in particular, from small gas turbines.

4 Paushkin, Ya., Sychev, R.V., Vishnyakova, T.P., and Zhomov, A.K. "The Influence of Chemical Composition and Mixtures on the Combustion of Fuel in Jet Engines," Sbornik Trudov, Mezhvuzovskiy Soveshchaniya Po Khimii Nefti, p 293, 1960 (Translation by Translation Services Branch, Foreign Technology Division, WP-AFB Ohio).

The fuel effects on combustion were studied in a laboratory combustion chamber operated at atmospheric pressure. The sooting characteristic was shown to increase with increasing aromatic hydrocarbon content.

- Pillsbury, P.W., et al., "Investigating Combustion Turbine Burner Performance With Coal Derived Liquids Having High Fuel Bound Nitrogen," ASME Paper 78-GT-126, April 1978.

The problems of fueling standard units with these liquids are being determined, with special emphasis on environmental aspects. Small-scale and full-scale laboratory combustor tests are described. Results from earlier tests are surveyed, especially with regard to smoke production, NO_x emissions, and flame radiation. A unique feature of the present program is the stress on developing surrogate petroleum-derived fuel to "stand-in" for scarce coal liquids during early development of the advanced burners needed to handle a broad range of coal liquids.

- Pillsbury, P.W., et al., "Fuel Effects in Recent Combustion Turbine Burner Tests of Six Coal Liquids," ASME Paper 79-GT-137, March 1979.

Comparative tests have been made in combustion turbine burners between six coal derived liquid (CDL) fuels and No. 2 distillate oil. All CDL fuels were evaluated in a half-scale (by diameter) combustor test rig, while one CDL fuel was also evaluated in a full scale high pressure combustion rig. The effects of these fuels on emissions of smoke and oxides of nitrogen, and on combustor metal temperature are discussed. Also observed in the testing were flame radiation, post-test combustor cleanliness, and emissions of carbon monoxide and hydrocarbons. Two of the CDLs do appear to be within the tolerance band which present combustion turbines can accept, with the exception of elevated NO_x emissions.

- Plee, S.L., et al., "Radiation and Smoke from Gas Turbine Flames, Part III," Technical Report No. 12349, March 1978.

Combustion efficiency, lean blowoff, smoke, flame radiation and spark ignition characteristics of gas turbine type flames are examined with particular emphasis on effects of alternate and synthetic fuels. Using a semi-empirical modeling technique, combustion efficiency and flame stabilization results have been linearly correlated for flames in which heterogeneous effects are negligible (light fuels). Modeling parameters include variations in combustor pressure, inlet temperature, geometry, air flow rate and reference velocity. This technique, which has proven successful in correlating combustion efficiency data from helicopter and automotive gas turbines, should also be applicable to the Army AGT-1500 engine for the XM-1 Main Battle Tank.

The effect of fuel properties (specifically aromatic content) on smoke and flame radiation is examined experimentally under operating conditions typical of modern gas turbine combustors.

- Prado, G.P., et al., "Soot and Hydrocarbon Formation in a Turbulent Diffusion Flame," Sixteenth Symposium (International) on Combustion, Aug 1976. p. 649-661.

Formation and emission of soot and polycyclic aromatic hydrocarbon (PCAH) from a turbulent continuous flow combustor have been studied. Measurements included mass concentration of both soot and PCAH, composition

of individual PCAH, and size distribution of soot particles, as a function of mixing intensity, fuel equivalence ratio and type of fuel (kerosene or benzene). Both soot and PCAH concentrations reach maxima early in the flame, after which PCAH decays rapidly and soot decays much slower. The maximum PCAH concentration always preceded that of soot in agreement with the concept that certain PCAH may serve as intermediates in soot formation. An approximate calculation based on the assumptions of local equilibrium with respect to soot formation and a Gaussian distribution of air-fuel mixedness gave satisfactory correlations of the data on soot formation at the higher cold gas velocity. At the lower velocity, the amount of soot and PCAH formed was drastically increased and strongly dependent on fuel atomization.

- Quigg, H.T., "Effect of Prevaporized JP-5 Fuel on Combustor Performance," Final Report, Naval Air Systems Command Contract N00019-71-C-0486, Phillips Petroleum Co. Res. and Dev. Report 6413-72, 1972.

An experimental investigation was conducted, using the Phillips 2-inch combustor operated under conditions simulating those in modern aircraft turbine engines, to determine effects of differences in JP fuels on flame radiance and exhaust emissions of nitrogen oxides, carbon monoxide, unburned hydrocarbon and soot. Kerosine-type fuels spanning the range in molecular structure (normal paraffins, isoparaffins, cycloparaffins, and aromatics) were evaluated. In initial studies the fuels were prevaporized to minimize effects of differences in their physical properties.

Empirical equations were developed for each of the five responses with the response expressed as a function of combustor pressure, inlet-air temperature, inlet-air humidity and fuels. It was concluded from the data obtained that total radiant energy and smoke emissions decrease with an increase in fuel hydrogen content.

A specification based upon a fundamental fuel property, such as hydrogen content, rather than a performance test, such as sooting tendency, offers additional advantages. Hydrogen content can be determined accurately by a variety of test methods, allowing selection of the best methods for research, process control, and product inspection from differing procedures and equipment. The basic guidance it provides to the petroleum chemist, with respect to the requirements of refinery processes for upgrading jet fuel burning quality, is not subject to misinterpretation.

- Roberts, R., Peduzzi, A., and Vitti, G.E. "Experimental Clean Combustor Program, Phase II, Alternate Fuels Addendum," NASA CR-134970, July 1976.

An alternate fuels investigation was conducted as an addendum to Phase II of the NASA Experimental Clean Combustor Program. The objective was to experimentally determine the impacts, if any, on exhaust emissions, performance, and durability characteristics of the Hybrid and Vorbix low-pollution combustor concepts when operated on test fuels which simulate composition and property changes which might result from future broadened aviation turbine fuel specifications or use of synthetically derived crude

feedstocks. The Vorbix concept exhibited significant increases in exhaust smoke with increasing fuel aromatic content.

Robertson, D.J., Elwood, J.H., and Groth, R.H., "Chemical Composition of Exhaust Particulates from Gas Turbine Engines," Report EPA-600/2-79-041, 1979.

The principal objective of this study was to determine the amount of polycyclic organic compounds and nitrosamines absorbed into the particulate matter. As a part of these tests, two fuels which were identical except for sulfur content were tested - one contained 0.00655% S and the other 0.25% S. Sulfur oxides measured by wet chemical techniques showed that a good material balance was obtained between fuel bound sulfur and the SO_2/SO_3 in the exhaust gases.

Robson, K., "The Influence of Changing Fuel Specification on Combustor Performance and Emission: A Review of Derby Test Experience," Rolls-Royce Aero Division Derby Report DP 353, March, 1979.

Smoke emissions will be affected by fuel type. Regulations should take this into consideration and a reference fuel may be needed for proving tests.

Schiefer, R.B., Gatzemeyer, J.B., and Dibelius, N.R. "Smoke Reduction in Residual-Fuel-Burning Gas-Turbine Combustion System", ASME Paper 60-GTP-7, 1960.

As a result of the requirement that a gas turbine-electric locomotive burning No. 6 fuel operate in areas where legislation prohibits operation if the smoke in the exhaust gases exceeds a specified amount, a program was undertaken to develop a combustion system which would meet the requirements without compromising the other performance criteria. This paper describes the physical and chemical nature of smoke, the objective measurement of smoke, the effect of operating variables on smoking tendency, and finally the considerations which led to a combustion-chamber design which met the requirements as evidenced by the engine test results.

Schirmer, R.M., "Specification of Jet Fuel Hydrogen Content for Control of Combustion Cleanliness," Progress Report No. 1, Navy BuWep Contract N600(19)-58219, Phillips Petroleum Co. Research Div. Report 3195-62R, Feature No. 6049, 1962.

A Critical analysis has been made of current test methods, Smoke Point and Luminometer Number, for evaluation of the burning quality of hydrocarbon fuels for aircraft gas turbine engines. Unfortunately, the laminar flow diffusion flame of the wick lamp differs appreciably from the highly turbulent combustion process in an aircraft gas turbine engine. Differences in the mechanism of soot formation, as evidenced by the effect of hydrocarbon structure, are discussed in detail. This can result in undue emphasis being placed upon the attainment of a jet fuel quality, such as a very high Luminometer Number, from which no significant benefit in terms of performance or durability can reasonably be expected.

Measurements of the cleanliness of aircraft gas turbine combustion processes, liner temperature and flame radiation, show a linear correlation with hydrogen content of the fuel. The cleanest burning fuels are those that contain the most hydrogen. A two- to fourfold improvement in repeatability and a fourfold improvement in reproducibility over current test methods should be feasible with hydrogen content. The use of hydrogen content for specification of jet fuel burning quality is recommended.

4 Schirmer, R.M., "Effect of Fuel Composition on Particulate Emissions From Gas Turbine Engines," in Emissions from Continuous Combustion Systems, edited by W. Cornelius and W. G. Agnew, Plenum Publishing Corp., New York, 1972.

A critical analysis has been made of the test methods, Smoke Point and Luminometer Number, which are used at present to evaluate the burning quality of hydrocarbon fuels for gas turbine engines. Differences in the mechanism of soot formation, between a wick lamp and a gas turbine combustor, as evidenced by the effect of hydrocarbon structure, are discussed in detail. Relevant information is reviewed on both the effect of smoke-abatement fuel additives and the morphology of particulate emissions. It is concluded that a specification based upon a fundamental fuel property, such as hydrogen content, rather than a performance test, such as sooting tendency, offers several advantages.

4 Shaffernocker, W.M., and Stanforth, C.M., "Smoke Measurement Techniques," SAE Paper 680346, April 1968.

The measurement of the smoking characteristics of jet engines and jet engine components is necessary to evaluate the relative merits of proposed methods of smoke reduction, identify sources, and estimate the visibility of the exhaust plume. Several techniques have been employed by the General Electric Co. to collect data over a wide range of environment.

Techniques evaluated included optical systems, quantitative gravimetric system, and soiled tape methods. Many of the soiled tape methods of measuring smoke are compared, and a calculation procedure is described for making a direct comparison of any two soiled tape methods.

The soiled tape method used by General Electric to measure jet engine smoke is described in detail. The measurement system utilizes a GE spot meter which filters the smoke through Whatman paper and produces a smoke number that is based upon the diffuse reflection from the filtrate produced by filtering 0.3 cu. ft of smoke through a square inch of filter paper.

4 Shayeson, M.W., "Reduction of Jet Engine Exhaust Smoke with Fuel Additives," SAE Paper 670866, 1967.

An investigation of fuel additives was conducted to identify materials which will reduce or eliminate jet engine exhaust smoke. Many materials were evaluated in a full-scale combustor rig, and the better ones were further tested in full-scale engines, both on the ground and in flight.

Several materials have been identified which, when added to JP-5 in low concentration, can greatly reduce jet engine exhaust smoke. The effectiveness of additives in reducing smoke is a function of engine design and power level. The formation of solid exhaust products in the combustion of fuel additive 2 causes no major adverse effects on J79 engine operation in 100 hours. Metallorganic compounds of barium, manganese, and iron are the most effective smoke reduction fuel additives found to date. The organic portion of the additive molecule apparently has some effect on its ability to reduce smoke.

- Stettler, R.J., and Hardin, M.C., "Initial Evaluation of Coal Derived Liquid Fuels in a Low Emission and Conventional Turbine Combustor," Presented at the Central States Section of the Combustion Institute, Spring Meeting, Columbus, Ohio, April 1976.

The combustion performance of three coal derived fuels was examined in both a regenerative low emission automotive turbine engine combustor and a nonregenerative conventional aircraft combustor. The three fuels were a UTAH light fraction, a blend of 20% Utah light and 80% UTAH heavy simulating a full range product and a topped full range product of UTAH and Illinois #6 coal. The low emission combustor was operated in both a low emission mode and mode simulating the conventional turbine combustor. Combustion efficiency under all conditions was above 99.5% and smoke was below the visible limit. The aircraft conventional combustion system was operated over the full power range. The combustor operation on the coal derived fuels compared to aircraft petroleum derived fuels indicated increased smoking believed due to increased aromatic content.

- Streets, W.L., "Characteristics of Flame Radiation of High Temperature Hydrocarbon Fuels," Phillips Petroleum Co. Research Division Report 2307-59R, Feature No. 6024, April 1959.

Investigation of the effects of a monocyclic and several polycyclic hydroaromatic high temperature hydrocarbon fuels on flame radiation and flame tube metal durability has been conducted in a two-inch laboratory scale combustor under simulated conditions of sea-level takeoff, medium altitude cruising and high loitering flight. Isoparaffinic and aromatic fuels were also included for reference purposes. Supplementary data obtained include deposition, smokiness, combustion efficiency, flame radiation in the Phillips Microburner and ASTM smoke point.

- Toone, B., "A Review of Aero Engine Smoke Emission," in Combustion in Advanced Gas Turbine Systems, Proceedings of an International Propulsion Symposium held at the College of Aeronautics, Cranfield, April 1967, Edited by I.E. Smith, Pergamon Press, Oxford.

Smoke measurement instruments and sampling techniques are discussed. The relative importance of fuel quality, burner characteristics, aerodynamic mixing in combustion chamber, and inlet conditions to smoke formation are examined. One conclusion is that the effect of fuel quality is small compared with changes which can normally be achieved by improving air and fuel mixing.

- Vaught, J.M., "The Effect of Inlet Temperature and Pressure on Industrial Turbine Engine Exhaust Emission," ASME paper 75-WA/GT-11.

The effect of variation of inlet temperature and pressure on exhaust emissions from an industrial gas turbine was determined experimentally. Testing was done in a controlled environment test cell. In addition to temperature and pressure, the influence of two fuels, JP-5 and DF-2, was evaluated. A data matrix of 81 engine operating points was obtained, from which emissions were correlated with engine inlet conditions using regression analysis techniques. The data are analyzed to show how these inlet variables affect compliance with the EPA exhaust emission standards for aircraft and stationary turbine engines.

SECTION III

Gaseous Emissions and Combustion Efficiency

Atomization and evaporation, which depend on fuel viscosity and volatility, are significant in controlling combustion only at ignition and lower power conditions. At higher power, variations in viscosity and volatility have a small or no effect on gaseous emissions and combustion efficiency. In some combustors, especially at idle, CO and HC levels increase with the final boiling point, indicating the effects of evaporation. Combustion efficiency is the highest with the lowest boiling range fuels, but at high power conditions the efficiency is quite high with all fuels. Many alternative fuels contain higher fuel nitrogen which leads to increased NO_x production, but the conversion efficiency depends on the fuel nitrogen concentration and the combustor inlet temperature.

- Ballal, D.R., and Lefebvre, A.H., "Combustion Efficiency of Gas Turbine Combustors Burning Alternative Fuels," AIAA Paper No. 78-1000, July 1978.

Equations for predicting and correlating the combustion efficiencies of gas turbine combustors are derived for conditions where the heat release is limited either by chemical reaction, mixing or evaporation, or by a combination of reaction and evaporation. Methods for calculating the critical mean drop size, $D(\text{crit})$, above which evaporation becomes the rate-controlling step are presented. It is shown that $D(\text{crit})$ increases with increase in combustion volume, combustion pressure, liner pressure drop and fuel volatility, and diminishes with increase in gas velocity. It is also shown that the ignition energy requirements of liquid hydrocarbon fuels are influenced mainly by their viscosity and volatility, which together govern the rate of fuel evaporation in the ignition zone.

- Blazowski, W.S., Fahrenbruck, F.S. and Tackett, L.P., "Combustion Characteristics of Oil Shale Derived Jet Fuels," Paper 75-13, Western States Section/Combustion Institute, Oct 1975.

This paper reports on investigation of jet fuels derived from Colorado oil shale deposits. Combustor rig testing was performed on both as-received and clay treated fuels using a T56 single combustor scaled to examine a wide variety of engine types. Higher fuel nitrogen content in both oil shale fuels was found to result in slightly increased NO_x emission. Further comparative testing using oil shale and petroleum JP-4 fuels in an afterburning J85-5 turbojet engine showed no performance differences, although a slight NO_x increase was detected at idle operation.

- Blazowski, W.S., "The Impact of JP4/JP8 Conversion on Aircraft Engine Exhaust Emissions," AFAPL-TR-76-20, May 1976.

JP4 and JP8 were evaluated in a T56 single can combustor test rig and a J85-5 engine. Changes in emission characteristics were measured and are reported. Projections of the impact of JP4 to JP8 conversion on military aircraft emissions are made.

- Blazowski, W.S., "Combustion Considerations for Future Jet Fuels," Sixteenth (International) Combustion Symposium, Boston, Aug 1976, The Combustion Institute.

T56 combustor rig tests were performed with test fuels consisting of JP4/Xylene blends (12.7 to 14.5 percent hydrogen by weight), high fuel bound nitrogen blends, and two oil shale derived JP4 fuels. Liner temperature, exhaust emissions, and smoke were measured and correlated with fuel properties and combustor operating conditions. Although smoke emission increased with decreased hydrogen content, gaseous exhaust emissions were unchanged. Fuel bound nitrogen conversion to NO_x under practical aircraft combustion conditions (up to 838°K inlet temperature) was found to be dependent on both fuel nitrogen concentration and combustor inlet temperature.

- Blazowski, W.S., and Jackson, T.A., "Evaluation of Future Jet Fuel Combustion Characteristics," AFAPL-TR-77-93, July 1978.

The impact of lower fuel hydrogen content on combustor liner temperatures, smoke, and gaseous emissions has been evaluated and improved correlations with hydrogen content have been developed. Fuel bound nitrogen-to- NO_x conversion in an aircraft gas turbine combustor has been evaluated. The conversion percent was found to decrease with increasing fuel nitrogen content or with increasing combustor inlet temperature.

- Blazowski, W.S., "Dependence of Soot Production on Fuel Blend Characteristics and Combustion Conditions," ASME Paper 79-GT-155.

A small scale laboratory device which simulates the strongly back-mixed conditions present in the primary zone of a gas turbine combustor is utilized. Presented are gaseous combustion product distributions for a variety of fuels. The influences of combustor inlet temperature and reactor mass loading have been evaluated.

- Blazowski, W.S., Sarofim, A.F., and Keck, J.C., "The Interrelationship Between Soot and Fuel NO_x Control in Gas Turbine Combustors," ASME-80-GT-76, 1980.

The decreased hydrogen content of future fuels will lead to increased formation of soot, while increased organically bound nitrogen in the fuel can result in excessive NO_x emission. Control concepts for these two problems are in conflict: prevention of soot requires leaner operation while control of emissions from fuel nitrogen requires fuel-rich operation. However, recent results of two DOE research programs point to both processes having a major dependence on "hydrocarbon breakthrough." Control of both fuel nitrogen conversion and soot formation can be achieved by primary zone operation at equivalence ratios just below that for hydrocarbon breakthrough. This paper reviews the evidence for the importance of hydrocarbon breakthrough, explains our current understanding of why hydrocarbon breakthrough is important, and offers suggestions of how these results might be applied.

- Butze, H.F., and Ehlers, R.C., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor," NASA TM X-71789, Oct 1975.

The performance of a single-can JT8D combustor was investigated with a number of fuels exhibiting wide variations in chemical composition and volatility. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons and NO_x, as well as liner temperatures and smoke. At the simulated idle condition no significant differences in performance were observed. No significant differences were observed in the performance of an oil-shale derived JP-5 and a petroleum-based Jet A fuel except for emissions of NO_x which were higher with the oil-shale JP-5. The differences is attributed to the higher concentration of fuel-bound nitrogen in the oil-shale JP-5.

- Butze, H.F., and Liebert, C.H., "Effect of Ceramic Coating of JT8D Combustor Liner on Maximum Liner Temperatures and Other Combustor Performance Parameters," NASA TM X-73581, Dec 1976.

The effect of ceramic coating of a JT8D combustor liner was investigated at simulated cruise and takeoff conditions with two fuels of widely different aromatic contents. Substantial decreases in maximum liner temperatures and flame radiation values were obtained with the ceramic-coated liner. Small reductions in exhaust-gas smoke concentrations were observed with the ceramic-coated liner. Other performance parameters such as combustion efficiency and emissions of unburned hydrocarbons, CO, and NO_x were not affected significantly. No deterioration of the ceramic coating was observed after about 6 hours of cyclic operation including several startups and shutdowns.

- Butze, H.F., and Smith, A.L., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor at Simulated Idle, Cruise, and Takeoff Conditions," NASA TM-73780, Sept 1977.

The performance of a single-can JT8D combustor was investigated with a number of fuels exhibiting wide variations in chemical composition and volatility. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons and NO_x, as well as liner temperatures and smoke. At the simulated idle condition, emissions of CO and unburned hydrocarbons increased slightly and, accordingly, combustion efficiencies decreased slightly as the hydrogen content of the fuels decreased.

- Butze, H.F., and Humenik, F.M., "Parametric Performance of a Turbojet Engine Combustor Using Jet A and a Diesel Fuel," NASA-TM-79089, March 1979.

The performance of a single-can JT8D combustor was evaluated with Jet A and a high-aromatic diesel fuel over a parametric range of combustor-inlet conditions. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons, and NO_x, as well as liner temperatures and smoke. At all conditions the use of diesel fuel instead of Jet A resulted in increases in smoke numbers and liner

temperatures; gaseous emissions, on the other hand, did not differ significantly between the two fuels.

- Carl, D.E., and Obidinski, E.S., and Jersey, C.A., "Exhaust Emissions from a 25-MW Gas Turbine Firing Heavy and Light Distillate Fuel Oils and Natural Gas," ASME Paper 75-GT-68, March 1975.

Heavy and light distillate fuel oils and natural gas were compared during this emissions test. As expected, the emissions using natural gas were normally much less than with No. 2 oil. The noteworthy differences of this test relate to the two distillate oils. There were no significant differences between the emission levels of NO_x , CO, or unburned hydrocarbons for the two. Using the heavy distillate oil, there were higher SO_2 emissions (which is in agreement with the fuel sulfur levels), lower smoke levels, and higher particulate levels than with No. 2 oil.

- Clark, J.A., et al., "Radiation/Smoke and Combustion Efficiency from Gas Turbine Flame, IV. Fuel Property Effects on Performance," PURDU-CL-79-05, March 1979. (USATARADCOM DAAE07-76-C-0063, Technical Report No. 12438).

The performance of gas turbine combustors with respect to combustion efficiency, flame stabilization, ignition, smoke and radiation, burning a wide range of fuel types is considered. The experimental portion of the program was conducted with a simplified combustor designed to yield apparatus independent results.

Combustion efficiencies for various fuels are discussed in terms of a semi-empirical model based on characteristic times which has proved successful for relatively "light" fuels. However, the results indicate that for less volatile and more viscous fuels the correlation of combustion efficiency is less acceptable.

- Clayton, R.M., "A Partial Oxidation Staging Concept for Gas Turbines Using Broadened Specification Fuels," ASME Paper 79-GT-169, March 1979.

A concept is described for using a very fuel-rich partial oxidation process as the first stage of a two-stage combustion system for onboard processing of broadened specification fuels to improve their combustion characteristics. Results of an initial step in the experimental verification of the concept are presented, where the basic benefits of H_2 enrichment are shown to provide extended lean-combustion limits and permit simultaneous achievement of ultralow levels of NO_x , CO, and HC emissions. The H_2 required to obtain these results is within the range available from a partial oxidation precombustion stage. Operation of a catalytic partial oxidation reactor using a conventional aviation turbine fuel (JP5) and an unconventional fuel (blend of JP5/xylene) is shown to produce a "fuel gas" stream with near-theoretical equilibrium H_2 content. However, a number of design considerations indicate that the precombustion stage should be incorporated as a thermal reaction.

- Colket, M.B., et al., "Radiation and Smoke from Gas Turbine Flames, Part II: Fuel Effects on Performance," PURDU-CL-77-01, 1977. (USATACOM DAAE07-76-C-0063).

Fuel effects upon gas turbine combustor performance, including combustion efficiency, lean blow off, smoke, and flame radiation, must be defined to minimize development efforts in adapting existing Army engines to synthetic and alternate fuels. Limited results for efficiency, blow off, and smoke concentrations are presented for a simulated combustor primary zone burning various fuels, and correlating schemes capable of collapsing the data for blow off and efficiency are refined. Preliminary flame radiation measurements have been obtained. Future tests required on all of the above performance parameters, as well as on spark ignition are suggested.

- Detroit Diesel Allison, "Model 501-K17 Gas Turbine Single Burner Evaluation of Shale Derived Marine Diesel Fuel," DDA EDR 8660, Jan 1976.

A significant quantity of crude oil has been extracted from Colorado oil shale in the Paraho project. This crude was subsequently experimentally refined to produce a broad range of military fuels. This report presents results obtained in gas turbine combustion tests of a marine diesel fuel from this project. A can-annular segment of the DDA 501-K17 marine gas turbine engine was used in the tests. Burner conditions simulated the operating spectrum experienced by this engine in the U.S. Navy DD963 class destroyers. Starting and steady state points from zero to full power were examined. The performance of the shale fuel was compared with the obtained at equivalent conditions with a petroleum marine diesel fuel from the U.S. Navy supplies.

The starting characteristics and combustion efficiencies obtained with the shale derived fuel were acceptable, and within the performance range expected for petroleum fuels to DOD Specification MIL-F-16884-G. The carbon monoxide and unburned hydrocarbon emissions from shale fuel operation were normal. However, the quantity of nitrogen oxides emitted was distinctly larger than obtained from petroleum fuel operation. The sharply increased NO_x is attributed to higher levels of nitrogen bearing compounds present in the shale fuel. Combustor design modifications to materially reduce the liquid fuel nitrogen conversion do not appear hopeful. Refining studies to reduce the nitrogen in the shale fuels are recommended.

- Dodds, W.J., Renie, J.P., and Mellor, A.M., "Gas Turbine Engine Stability and Performance as Determined by Fuel and Injector Type," USATACOM Report No. 12065, Purdue Report No. PURDU-CL-75-05 1975.

In order to establish the versatility of the gas turbine combustor in utilizing non-specification fuels such as those expected to be derived from refinement of oil shale and liquefaction of coal, an experimental program has been initiated to determine the effects of fuel and injector type on the spray combustion process. The initial phase of this is an exploratory study of combustion efficiency and stability for two fuels, Jet A and #5 fuel oil, injected through two different pressure atomizing nozzles. Data correlation techniques including both the use of traditional correlating parameters and a characteristic time model of the spray combustion process are discussed and compared. Using these correlating parameters, combustion

efficiency and stability data taken for Jet A fuel and #5 fuel oil in the laboratory combustor are compared with similar data taken in a T-63 combustor (Moses, 1975), showing applicability of simplified test combustor data to actual combustors. Data for Jet A fuel injected through two different nozzles indicates that both stability and efficiency are adversely affected by increased droplet lifetime; however further increasing calculated droplet lifetime by the use of #5 fuel oil produced no further decrease in measured combustion efficiency and resulted in improved stability at the lean limit. Several explanations for these results are examined, with emphasis on possible measurement errors and changes in physical phenomena which may occur in the evaporation of large droplets. Oxides of nitrogen emissions data are presented which show a significant increase in NO_x formed using the #5 fuel oil.

- Ekstedt, E.E., and Macaulay, R.W., "Combustion of Heavy Distillate Fuel for the LM2500 Gas Turbine," ASME 72-GT-24, Jan 1973.

The combustor for the LM2500 is an annular combustor developed for use with marine and industrial fuels including natural gas and heavy distillates. This paper relates the development of this combustor including some of the design criteria, the fuel properties and some of the combustor performance results such as exit gas temperature patterns, ignition, pressure loss, and efficiency. Investigations have included a wide range of fuels and several fuel injector designs. The engine has operated in GTS Adm. Wm. M. Callaghan for a total of more than 10,000 hrs with no combustor problems, smoke carbon, life or otherwise.

- Gleason, C.C., and Bahr, D.W., "Alternate Fuels Addendum, Phase II. Experimental Clean Combustor Program," NASA CR-134972, Jan 1976.

A study was conducted to investigate the characteristics of current and advanced low-emissions combustors when operated with special test fuels simulating broader ranges of combustion properties of petroleum or coal-derived fuels. Five fuels were evaluated; conventional JP-5, conventional No. 2 Diesel, two different blends of Jet A and commercial aromatic mixtures - "xylene bottoms" and "naphthalene charge stock", and a fuel derived from shale oil crude which was refined to Jet A specifications. Three CF6-50 engine size combustor types were evaluated; the standard production combustor, a Radial/Axial Staged Combustor, and a Double Annular Combustor. Performance and pollutant emissions characteristics at idle and simulated takeoff conditions were evaluated in a full annular combustor rig. For the five fuels tested, effects were generally quite moderate, but well defined. CO , HC , NO_x and smoke emissions levels and peak liner metal temperatures increased with decreasing hydrogen content of the fuel which ranged from 12.2 to 13.7 percent by weight. CO , HC and smoke emissions levels also increased with final boiling point of the fuel which ranged from 529 to 607° K. Effects on other characteristics were quite small.

- Gleason, C.C., and Bahr, D.W., "Experimental Clean Combustor Program Diesel No. 2 Fuel Addendum, Phase III Final Report," NASA CR-135413, 1979.

A CF6-50 engine equipped with an advanced, low emission, double annular combustor was operated 4.8 hours with No. 2 diesel fuel. Fourteen steady-state operating conditions ranging from idle to full power were investigated. Engine/combustor performance and exhaust emissions were obtained and compared to JP-5 fueled test results. With one exception, fuel effects were very small and in agreement with previously obtained combustor test rig results. At high power operating condition, the two fuels produced virtually the same peak metal temperatures and exhaust emission levels. At low power operating conditions, where only the pilot stage was fueled, smoke levels tended to be significantly higher with No. 2 diesel fuel. Additional development of the combustor concept is needed in the areas of exit temperature distribution, engine fuel control, and exhaust emission levels before it can be considered for production engine use.

- Gleason, C.C., et. al., "Evaluation of Fuel Character Effects on the J79 Engine Combustion System," AFAPL-TR-79-2015, June 1979.

Results of a program to determine the effects of broad variations in fuel properties on the performance, emissions, and durability of the J79-17A turbojet engine combustion system are presented. Combustor tests conducted at engine idle, takeoff, subsonic cruise, supersonic dash, cold day ground start, and altitude relight operating conditions with 13 different fuels are described. The test fuels covered a range of hydrogen contents (12.0 to 14.5 percent), aromatic type (monocyclic and bicyclic), initial boiling point (285 to 393 K), final boiling point (552 to 679K) and viscosity (0.83 to 3.25 mm²/s at 300K).

At high power operating conditions, fuel hydrogen content was found to be a very significant fuel property with respect to liner temperature, flame radiation, smoke, and NO_x emission levels. Carbon monoxide and HC emissions were very low at these conditions with all of the fuels. At engine idle operating conditions, CO, HC, and NO_x emission levels were found to be independent of fuel hydrogen content, but a small effect of fuel volatility and/or viscosity was found.

- Gleason, C.C., et al, "Evaluation of Fuel Character Effects on F101 Engine Combustion System, Final Report," AFAPL-TR-79-2018, June 1979.

Results of a program to determine the effects of broad variations in fuel properties on the performance, emissions and durability of the General Electric F101 augmented turbofan engine main combustion system are presented. Combustor rig tests conducted at engine idle, takeoff, cruise, dash, cold day ground start and altitude relight operating conditions with 13 different fuels are described. Fuel nozzle fouling tests conducted with the same fuels are also described. The test fuels covered a range of hydrogen contents (12.0 to 14.5%), aromatic type (monocyclic and bicyclic), initial boiling point (285 to 393 K), final boiling point (552 to 679 K) and viscosity (0.83 to 3.25 mm²/s at 300K).

At high power conditions, fuel hydrogen content was found to have a very significant effect on liner temperature, smoke, and NO_x levels. At

idle conditions, CO and HC levels correlated with fuel atomization/volatility parameters, but showed no relationship to hydrogen content.

- Gleason, C.C., and Martone, J.A., "Fuel Character Effects on J79 and F101 Engine Combustor Emissions," ASME 80-GT-70, 1980.

Results of a program to determine the effects of fuel properties on the pollutant emissions of two US Air Force aircraft gas turbine engines are presented. Thirteen test fuels, including baseline JP-4 and JP-8, were evaluated in a cannular (J79) and a full annular (F101) combustor. The principal fuel variables were hydrogen content, aromatic structure, volatility, and distillation end point. Data analysis shows that fuel hydrogen content is a key fuel property, particularly with respect to high power emissions (oxides of nitrogen and smoke), and that low power emissions (carbon monoxide and hydrocarbons) are more dependent on fuel atomization and evaporation characteristics.

- Hammond, D.C., "Operation of a GT-225 Diffusion-Flame Combustor on Alternative Fuels Performance, Durability and Emissions," ASME Paper 79-GT-138, March 1979.

Ten fuels were burned in a GT-225 diffusion-flame combustor and the performance, durability, and emissions evaluated. These fuels were: reference kerosene, three petroleum distillates, two alcohols, one coal-derived fuel, a fuel made from tar sands, and two fuels made from oil shale. All of the fuels were burned without modifying either combustor or fuel nozzle. The more volatile petroleum distillates burned more efficiently than kerosene. The alcohols and the more viscous synthetic fuels exhibited combustion efficiencies slightly lower than that of kerosene, possibly as a result of poorer initial atomization. The synthetic fuels having high aromatic contents produced higher flame-tube-wall temperatures than did kerosene, but not sufficiently high to reduce durability. The emissions from the combustion of all petroleum distillates were comparable to those of kerosene. The alcohols gave 60 to 80 percent lower oxides of nitrogen emissions, up to 650 percent higher carbon monoxide emissions and up to 300 percent higher total hydrocarbon emissions than kerosene, but these emissions were considerably reduced by increasing atomizing-air differential pressure to the injector. Some of the synthetic fuels contained large amounts of nitrogen and substantial oxidation of it was evidenced. The most viscous synthetic fuels exhibited carbon monoxide and total hydrocarbon emissions 100 percent higher than kerosene.

- Hardin, M.C., and Stettler, R.J., "Initial Evaluation of Coal Derived Liquid Fuels in a Low Emission Turbine Combustor," General Motors Report, Engineering Publication A-3161, Sept 1974.

A low emission combustor was tested with liquid coal fuels at a regenerative automotive gas turbine operating condition. Combustor performance was measured on three liquid coal fuels from the COED (coal-oil-energy-development) process. The three fuels were a UTAH light fraction, a blend of 20% UTAH light and 80% heavy simulating a full range

product and a topped full range product of Illinois #6 coal. The low emission combustor was operated in both a low emission mode and a mode simulating the conventional turbine combustor. In both modes of operation, high oxides of nitrogen were recorded. An analysis of the fuel bound nitrogen indicates that this nitrogen may have contributed heavily to the high oxides of nitrogen in the combustor exhaust. Combustion efficiency under all conditions was above 99.5%.

- Hardin, M.C., "Evaluation of Three Coal Derived Liquid Fuels in a Standard T63 Combustor," Detroit Diesel Allison Report RN74-28, Nov 1974.

The combustion performance of three coal derived fuels was examined in a standard gas turbine engine combustor. The fuels were crude materials of varying volatility levels produced by FMC Corporation's COED process. The combustion performance, as measured by combustion efficiency, varied from excellent at 100% speed to acceptable at operational idle conditions.

- Hazard, H.R., "Conversion of Fuel Nitrogen to NO_x in a Compact Combustor," 1973 ASME Annual Meeting, Detroit, Mich., Nov 1973.

A low nitrogen fuel, ASTM Jet A aviation kerosene, was doped with increasing amounts of pyridine as a means of increasing the content of chemically bound nitrogen, then burned at a rate of 50 lb/hr in a compact combustor incorporating staged air admission with a rich primary zone, and water cooling of the walls. Each increase in fuel nitrogen content resulted in a significant increase in NO_x in the combustion products, and it is estimated that as much as 90 percent of the fuel nitrogen was converted to NO_x at very low nitrogen levels, decreasing to 55 percent conversion at higher levels. These results are consistent with data reported for large steam boilers and for small residential boilers. It appears that emission standards requiring very low levels of NO_x emission will require use of fuels with very low nitrogen content.

- Horstman, W.W., and Jackson, J.L., "Combustion Characteristics of Special Hydrocarbon Jet Fuels," ASD TDR-62-682 WPAFB, 1962.

A single combustor from a General Electric J-79 engine was used to evaluate combustion efficiency, flame radiation, fuel consumption, and altitude relight characteristics of twelve hydrocarbon fuels. Selection of fuels was based primarily on heat of combustion, density, Luminometer Number, and thermal stability for potential use in supersonic aircraft gas turbine engines. Tests were made with simulated Mach 1.5, 2, 2.5, and 3 speeds at 80,000 feet altitude, and a high combustor severity condition at the maximum compressor output.

The relative combustion efficiency was approximately constant for all fuels at a given test condition but increased about 9% as the combustion intensity was increased from 82,000 to 295,000 Btu/cu ft/min. An inverse linear relationship existed between fuel heat of combustion and fuel consumption at a constant burner temperature rise. The fuel consumption also correlated with fuel composition.

- Hung, W.S.Y., "A Diffusion Limited Model that Accurately Predicts the NO_x Emissions from Gas Turbine Combustors Including the Use of Nitrogen Containing Fuels," ASME Paper 75-Pwr-11, Oct 1975.

A diffusion limited model has been described previously to simulate accurately the thermal NO_x emission processes in various gas turbine combustors for fuels containing negligible amounts of fuel bound nitrogen. The application of this model to simulate accurately the water injection process has also been demonstrated. It is currently proposed that any bound nitrogen in fuel is completely reacted to form nitric oxide during the hydrocarbon combustion process; the ultimate net conversion is determined subsequently based on the Zeldovich mechanisms. With this additional assumption, this model has been generalized to include the use of fuels containing significant amounts of bound nitrogen, such as crude or residual oils.

- Hung, W.S.Y., "Modeling and Measurement of NO_x Emissions from Burning Synthetic Coal Gas in Gas Turbine Combustors," ASME Paper 75-WA/GT-3, Nov 1975.

A diffusion limited model has been described previously to simulate accurately the thermal NO_x emission processes in various gas turbine combustors for fuels containing negligible amounts of fuel bound nitrogen. This model has been extended to simulate the combustion of synthetic coal gas turbine combustors. The predicated NO_x emissions from burning these low heating value gaseous fuels in full-scaled gas turbine combustors are in agreement with available laboratory data. The NO_x emission levels from burning various low heating value gaseous fuels in the 100-300 Btu/scf (3.73-11.2 MJ/scm) range have been predicated. It has been shown in the current analysis that the heating value of a fuel is not necessarily an indicator of its NO_x emissions. The peak temperature resulting from the combustion of the fuel is the primary parameter that determines the NO_x emission level. There are fuels in the 200-300 Btu/scf (7.46-11.2 MJ/scm) range that will burn and generate significant NO_x emissions.

- Hung, W.S.Y., "The NO_x Emission Levels of Unconventional Fuels for Gas Turbines," ASME Paper 77-GT-16, March 1977.

An experimentally verified NO_x emission model for gas turbines has been reported previously. The model has been modified to determine the NO_x emission levels of various fuels as compared to No. 2 distillate oil. The NO_x emission levels of various conventional and unconventional gas turbine fuels of interest are predicted. The predicated NO_x emission levels for these fuels, including methanol, ethanol, propane, and hydrogen are in good agreement with available laboratory and field data from stationary, aircraft, and automotive gas turbine combustors. The predicted results should be applicable to other fuel-lean, heterogeneous combustion systems.

- Hunter, S.C., et al., "Advanced, Small, High-Temperature-Rise Combustor Program," Final Report, Volume I, USAAMRDL Tech Report 74-3A Feb 1974.

This report describes an analytical and experimental study of advanced, small, high-temperature combustors. The objectives of the 32-

month program were

a. To develop and validate an analytical design technique for small, high-temperature-rise, low-airflow combustors and related components

b. To define the limitations associated with these small combustors and related components and the effects of these limitations on the cycle and the configuration of advanced-technology engines

Analytical models were developed to predict the characteristics and performance of the basic combustor elements, including fuel injection, primary zone, dilution zone, and liner cooling. Nine combustor element rig test programs were conducted to provide data to update and validate the analytical models. Based on the analysis and rig test results, a full-scale combustor was designed, fabricated, and tested. An ancillary material screening program was conducted to select the most suitable existing material for combustor application. A relatively new material (IN-586) was selected. Material-property tests were conducted to supplement published data for this material.

The analytical models were used to assess combustor design and performance limitations and the applicability of the design techniques over an airflow range of 2 to 5 pounds per second, cycle pressure ratio range of 10 to 16 (including recuperation), and a turbine inlet temperature range of 2300°F to 2700°F.

Multifuel capability was examined including MIL-T-5424, Grades JP-4 and JP-5, MIL-T-83133, Grade JP-8, and Aviation Turbine Fuel, ASTM D1655-67 Type A-1.

Ingebo, R.D., and Norgren, C.T., "Combustor Exhaust Emissions and Blowout Limits with Diesel Number 2 and Jet A Fuels Utilizing Air Atomizing and Pressure Atomizing Nozzles," NASA-TM-X-71803; E-8483, 1975. Presented at Western States Section of the Combustion Institute, Palo Alto, Calif., Oct 1975.

Experimental tests with diesel number 2 and Jet A fuels were conducted in a combustor segment to obtain comparative data on exhaust emissions and blowout limits. An air-atomizing nozzle was used to inject the fuels. Tests were also made with diesel number 2 fuel using a pressure-atomizing nozzle to determine the effectiveness of the air-atomizing nozzle in reducing exhaust emissions. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air total pressures and temperatures of 41 to 203 newtons per square centimeter and 477 to 811 K, respectively, and a reference velocity of 21.3 meters per second. Smoke number and unburned hydrocarbons were twice as high with diesel number 2 as with Jet A fuel. This was attributed to diesel number 2 having a higher concentration of aromatics and lower volatility than Jet A fuel. Oxides of nitrogen, carbon monoxide, and blowout limits were approximately the same for the two fuels. The air-atomizing nozzle, as compared with the pressure-atomizing nozzle, reduced oxides-of-nitrogen by 20 percent, smoke number by 30 percent, carbon monoxide by 70 percent, and unburned hydrocarbons by 50 percent when used with diesel number 2 fuel.

Ingebo, R.D., and Norgren, C.T., "Combustor Exhaust Emissions with Air-Atomizing Splash-Groove Fuel Injectors Burning Jet A and Diesel Number 2 Fuels," NASA TMX-3255, July 1975.

Air-atomizing splash-groove injectors, utilizing fuel jets impinging against a grooved face, gave improved primary-zone fuel spreading and reduced combustor exhaust emissions for Jet A and diesel number 2 fuels. These conditions included fuel-air ratios of 0.008 to 0.018, inlet-air pressures of 41 to 203 N/cm², inlet-air temperatures of 477 to 811 K, and a reference velocity of 21.3 m/sec. With Jet A fuel large-orifice splash-groove injectors reduced the oxides-of-nitrogen emission index to 15, a value 25 percent less than that for previously tested air-atomizing splash-cone nozzles, but did not reduce emissions of carbon monoxide, unburned hydrocarbons, or smoke (at 700 K, 203 N/cm², and an 0.018 fuel-air ratio). Small-orifice splash-groove injectors did not reduce oxides of nitrogen but reduced the smoke number to 11 or by 45 percent (at 700 K, 101 N/cm², and an 0.018 fuel-air ratio) and reduced carbon monoxide and unburned-hydrocarbon emission indices to 35 and 12, or by 20 and 30 percent, respectively (at 477 K, 41 N/cm², and an 0.008 fuel-air ratio). With diesel number 2 fuel, the small-orifice splash-groove injector (compared with pressure-atomizing nozzles) reduced oxides of nitrogen by 19 percent, smoke number by 28 percent, carbon monoxide by 75 percent, and unburned hydrocarbons by 50 percent. Smoke number and unburned hydrocarbons were twice as high with diesel number 2 as with Jet A fuel.

Khan, M.R., and Newhall, H.K., "The Influence of Fuel Hydrocarbon Composition on Nitric Oxide Emissions," Central States Section Meeting of The Combustion Institute, March 1972.

The influence of engine fuel hydrocarbon composition on nitric oxide formation has received relatively little detailed attention. Results of an earlier theoretical study were based on chemical equilibrium principles with the implicit assumption that nitric oxide concentrations in the engine combustion process approach peak temperature equilibrium levels.

More recently it has been demonstrated that under most conditions of engine operation the formation of nitric oxide is kinetically limited due to quenching of formation reactions during the expansion process. Therefore while the foregoing equilibrium calculations are directionally correct in predicting changes in nitric oxide emissions with fuel composition changes, the magnitude of these predicted changes may differ substantially from those actually dictated by the rate limited formation process.

In particular for chemically correct and fuel-lean combustion products, equilibrium calculations markedly underestimate the effect of combustion temperature on nitric oxide emission levels.

The present results are based on calculation of the rate of nitric oxide formation in products of combustion representative of a number of pure hydrocarbon fuels of varied composition. Thus comparisons among fuels are made on the basis of nitric oxide formation rates rather than on the basis of chemical equilibrium nitric oxide concentration as in previous studies.

¹ Kuhbach, C.M., Ritcheske, W.F., and Strauss, K.H., "Properties and Jet Engine Combustor Performance," SAE Paper presented at the SAE National Aeronautic Meeting, Los Angeles, Volume 63, 1955.

How commercially available fuels behave in typical aircraft gas turbine combustors was the subject of the investigation discussed in this paper. Data were obtained on full-scale combustion chambers using a wide variety of fuels, with emphasis placed on combustion efficiency and deposit formation.

At low altitudes, combustion efficiencies are high and unaffected by heat output or fuel. An increase in altitude results in an efficiency decrease which is affected by type of fuel under certain conditions.

² Lefebvre, A.H., Mellor, A.M., and Peters, J.E., "Ignition/Stabilization/Atomization: Alternative Fuels in Gas Turbine Combustors," Edited by Craig T. Bowman and Jorgen Birkeland, Vol. 62, of Progress in Astronautics and Aeronautics. American Institute of Aeronautics and Astronautics Inc., New York, 1978, p. 137.

It is pointed out that fuel preparation, ignition, flame spreading, and flame stabilization are important considerations in the design of gas turbine engines. It is discussed how changes in the major properties of alternative fuels will affect atomization, ignition, flame spread, and lean blowoff in gas turbine burners. It is found that it is primarily the physical properties of the fuel which influence the performance parameters. Studies have shown that ignition is strongly dependent on fuel volatility and viscosity. A graph showing the influence of atomization quality on ignition limits is presented. For all fuels considered the atomization quality is found to be markedly inferior to that of normal kerosene, indicating that problems of ignition and lean blowoff will be more severe. The correlations predict that jet fuels derived from shale oils, tar sands, and coal syncrudes will pose more serious problems of atomization than similar petroleum-based fuels.

³ Lipfert, F.W., "Impact of Alternate Fuels on Stationary Gas Turbine Operations and Siting," ASME Paper 74-GT-154, March 1974.

An analysis of gas turbine ambient air quality impact is presented, from the standpoint of the acceptability of alternate fuels having higher sulfur content and possibly higher particulate emissions. Various plume rise formulas are compared, and formulas are given for maximum ground level concentrations for both short term (1 to 3 hr) and intermediate (3 to 24 hr) periods. The results show that the U.S. Federal Air quality standards may allow large gas turbine complexes (500 MW) burning up to 1% sulfur fuel, for example. Taking advantage of this capability could increase the supply of lower sulfur fuels for home heating and/or transportation use.

⁴ Lohmann, R.P., Szetela, E.J., and Vranos, A., "Analytical Evaluation of the Impact of Broad Specification Fuels on High Bypass Turbofan Engine Combustors," NASA CR-159454, PWA 5565-15, Dec 1978.

The impact of the use of broad specification fuels on the design, performance durability, emissions and operational characteristics of combustors for commercial aircraft gas turbine engines was assessed. Single stage, vortex and lean premixed prevaporized combustors, in the JT9D and an advanced energy efficient engine cycle were evaluated when operating on Jet A and ERBS (Experimental Referee Broad Specification) fuels. Design modifications, based on criteria evolved from a literature survey, were introduced and their effectiveness at offsetting projected deficiencies resulting from the use of ERBS was estimated. The results indicate that the use of a broad specification fuel such as ERBS, will necessitate significant technology improvements and redesign if deteriorated performance, durability and emissions are to be avoided. Higher radiant heat loads are projected to seriously compromise liner life while the reduced thermal stability of ERBS will require revisions to the engine-airframe fuel system to reduce the thermal stress on the fuel. Smoke and emissions output are projected to increase with the use of broad specification fuels. While the basic geometry of the single stage and vortex combustors are compatible with the use of ERBS, extensive redesign of the front end of the lean premixed prevaporized burner will be required to achieve satisfactory operation and optimum emissions.

Marchionna, N., Watkins, S. and Opdyke, G., "Turbine Fuel Tolerance Study," Technical Report No. 12090 (USATACOM DAAE07-74-C-0274), Oct 1975.

An exploratory program was undertaken to burn heavy distillate and residual fuel oils in a modified AGT 1500 gas turbine combustor. Combustor development utilized a new liner design and airblast fuel injector. The design approach was supported by water table modeling, nozzle spray analysis, and combustor tests. At combustor inlet air conditions of one atmosphere and 250°F, efficiency with the final design approached 95 percent with DF-2 and No. 4 oil. The combustor was also able to burn No. 6 oil but at a low efficiency.

Data obtained from a laser technique to measure droplet sizes were found to conform well with the Rosin-Rammler distribution function $R = \exp(-bx^q)$. The parameters b and q may be predictable from fuel injector operation parameters plus the physical characteristics of the fuel. An analytical model of droplet vaporization was used to predict efficiency for the final design with comparatively good results.

Marchionna, N.R., et al., "Turbine Fuel Tolerance Study, Initial Engine Test: No. 4 Oil," USATARADCOM Technical Report No. 12272, April 1977.

An AGT 1500 vehicular gas turbine engine was operated on No. 4 residual oil using a specially modified combustor. Combustion efficiency was over 99 percent at idle and over 99.9 percent at full power.

Marchionna, N., "Turbine Fuel Tolerance Study: Multifuel Engine Tests," USATARADCOM Technical Report 12392 (USATARADCOM DAAE07-74-C-0274) July 1978.

An AGT 1500 vehicular gas turbine engine was tested for multifuel capability. Overall performance did not vary when operating on JP-4, DF-2,

or unleaded gasoline. Combustion efficiency was over 99.5 percent at higher power settings.

4 Mellor, A.M., "Simplified Physical Model of Spray Combustion in a Gas Turbine Engine," Combustion Science and Technology 8, 101, 1973.

Heterogeneous processes have been identified as important in determining levels of exhaust emissions from liquid-fueled gas turbine engines. From correlations of NO and CO emissions indices with differential fuel injection pressure, a simplified physical model of the spray combustion process in a turbine combustor has been developed. This model not only is consistent with previous experimental data obtained in this laboratory, but also assists in understanding the successes and failures of analytical combustor models available in the open literature.

5 Moses, C.A., "Studies of Fuel Volatility Effects on Turbine Combustor Performance," 1975 Spring Meeting of Western and Central Sections of Combustion Institute.

An exploratory investigation has been made concerning the effects that the boiling-point-distribution of the fuel can have on turbine-combustor performance, in particular ignition, stability, exhaust emissions, and combustion efficiency. The experiments were conducted in a 5-atmosphere combustor rig based on T-63 engine hardware. Four fuels were used covering the range of viable fuels (JP-4 to #5 fuel oil). Efficiency and stability showed a definite ranking according to the boiling range with the lighter fuels being superior.

6 Moses, C.A., and Naegeli, D.W., "Effects of High Availability Fuels on Combustor Properties," AFLRL Report No. 101, AD-A054229, Jan 1978.

A high pressure and temperature research combustor was operated over a matrix of conditions involving

- a. burner inlet pressure, BIP = 2, 5, 10 and 15 atm,
- b. burner inlet temperature, BIT = 532, 812 and 1034°K,
- c. fuel/air ratio (heat input rate), H = 212, 424 and 848 KJ/Kg of air, and
- d. reference velocity (turbulence and residence time), V = 22, 44 and 66 M/sec.

Six petroleum base JP-5 fuels (principally atomatic blends) and three JP-5 syncrudes (from oil shale, coal and tar sands) were examined. NO_x and CO emissions were essentially the same for all fuels; the syncrude from oil shale containing fuel bound nitrogen gave higher NO_x. Combustion efficiency was very high, above 99%.

7 Moses, C.A., and Naegeli, D.W., "Fuel Property Effects on Combustor Performance," ASME Paper 79-GT-178, March 1979.

Two combustor rigs have been used to study the sensitivity of combustor performance to the physical and chemical properties of fuels.

The purpose was to determine the impact of broadening fuel specifications and using non-specification fuels in emergencies. Nineteen fuels including synfuels were used to accentuate the properties of concern: composition, viscosity, and boiling point distribution. The combustors were instrumented for flame radiation, liner temperature, and exhaust emissions; testing included ignition, stability, and combustion efficiency. Combustion efficiency, CO and UBH were dependent more on the high end of the distillation curve than on viscosity. NO_x was most sensitive to front end volatility.

- Naegeli, D.W., and Moses, C.A., "Effects of Fuel Properties on Soot Formation in Turbine Combustion," SAE Paper 781026, 1978.

A T-63 combustor rig has been used to study the sensitivity of combustor performance to the physical and chemical properties of fuels. The purpose was to determine the impact of broadening fuel specifications and using non-specification fuels in emergencies. The fuel properties of special concern were the composition, the distillation curve and viscosity. The first property is associated with the chemistry of carbon formation while the latter two are related to mixing as they affect the atomization and vaporization. The combustor was instrumented for the flame radiation, exhaust smoke and gaseous emissions. Measurements of these items were made at the full power condition.

- Opdyke, G., "The Effect of a Sample Lot of Fuel Injectors on Emissions Levels of a Small Gas Turbine," ASME Paper presented at the ASME 24th International Gas Turbine Conference, March 1979, San Diego, ASME Paper 79-GT-165.

A single small gas turbine engine, containing an annular combustor producing nearly conventional emission levels, was sampled for gaseous emissions and smoke a total of 20 times in a one month period. Five samples each of two fuel injector designs were tested in random order, and the combustor angular orientation was varied with respect to the compressor. In addition to the basic tests with aviation kerosene fuel, emission measurements were also made with Avgas and diesel fuel with each injector design. Fuel spray drop size distributions were estimated from sample test data.

The result of changing the fuel injector was the production of a significant variation in hydrocarbon and carbon monoxide emissions, with limited variation in oxides of nitrogen and smoke. After correction for ambient and operating conditions, the standard deviation in the EPA parameter for hydrocarbons was about 30% of the average value and 15% of the average value for carbon monoxide. It was postulated that the variation was caused by fuel injector manufacturing tolerances which resulted in large variations in the maximum drop size in individual sprays causing variable entrainment of unvaporized drops in the wall cooling film. The conclusion is that small, and perhaps non-detectable, variations in injectors can cause changes in emissions from gas turbines, and, in particular, from small gas turbines.

- Paushkin, Ya., et al., "The Influence of Chemical Composition and Admixtures on the Combustion of Fuel in Jet Engines," Sbornik Trudov, Mezhdvuzovskiy Soveshchaniya Po Khimii Nefti, p 293, 1960 (Translation by Translation Services Branch, Foreign Technology Division, WP-4AFB Ohio).

The fuel effects on combustion were studied in a laboratory combustion chamber operated at atmospheric pressure. The combustion efficiency increases in the following series of hydrocarbons: dicyclic aromatics < monocyclic aromatics < monocyclic aromatics with side chains < dicyclic naphthenes < cycloolefins < monocyclic naphthenes < paraffins.

- Pillsbury, P.W., et al., "Investigating Combustion Turbine Burner Performance with Coal Derived Liquids Having High Fuel Bound Nitrogen." ASME Paper 78-GT-126, 1978.

The problems of fueling standard units with these liquids are being determined, with special emphasis on environmental aspects. Small-scale and full-scale laboratory combustor tests are described. Results from earlier tests are surveyed, especially with regard to smoke production, NO_x emissions, and flame radiation. A unique feature of the present program is the stress on developing surrogate petroleum-derived fuel to "stand-in" for scarce coal liquids during early development of the advanced burners needed to handle a broad range of coal liquids.

- Pillsbury, P.W., et al., "Fuel Effects in Recent Combustion Turbine Burner Tests of Six Coal Liquids," ASME Paper 79-GT-137, March 1979.

Comparative tests have been made in combustion turbine burners between six coal derived liquid (CDL) fuels and No. 2 distillate oil. All CDL fuels were evaluated in a half-scale (by diameter) combustor test rig, while one CDL fuel was also evaluated in a full scale high pressure combustion rig. The effects of these fuels on emissions of smoke and oxides of nitrogen, and on combustor metal temperature are discussed. Also observed in the testing were flame radiation, post-test combustor cleanliness, and emissions of carbon monoxide and hydrocarbons. Two of the CDLs do appear to be within the tolerance band which present combustion turbines can accept, with the exception of elevated NO_x emissions.

- Plee, S.L., Schmidt, D.A., and Mellor, A.M., "Flame Efficiency, Stabilization and Performance in Prevaporizing/Premixing Combustors," PURDU-CL-77-07, Dec 1977. (Air Force Office of Scientific Research AFOSR 76-2936).

Problems of combustion efficiency, incomplete prevaporization and flame stabilization (blowoff and/or flashback) associated with advanced prevaporizing/premixing turbojet combustors, afterburners and ramjet combustors are examined experimentally using a simplified axisymmetric burner. This flameholder configuration retains the same fundamental combustion processes of prevaporizing/premixing combustors while eliminating some of the complexity of the practical hardware. In addition to variations in combustor pressure, inlet temperature, equivalence ratio and air velocity typical of modern combustors, geometry and heterogeneous effects are also considered.

Both flame stabilization and combustion efficiency data are examined using conventional (Lefebvre, 1966) and characteristic time (Mellor, 1976), correlations. Characteristic times, which have already been used to correlate and predict gaseous emissions in conventional combustors, are quantified here for blowoff. The model is based on the flame stabilization theory of Zukoski and Marble (1956) and includes inlet, geometry and heterogeneous effects simultaneously, unlike traditional loading parameters. Combustion efficiency data obtained for this study are not yet included in the correlation. Detailed internal species concentration, temperature and velocity measurements are planned to help identify proper scaling parameters for the combustion efficiency model.

Flame flashback into the fuel preparation tube has not been observed for any of our operating conditions. These results are consistent with a recent literature review (Plee and Mellor, 1977) which has identified important mechanisms of upstream flame propagation. This study shows that flow disturbances rather than combustor inlet conditions are responsible for the "flashback" reported in non-catalytic combustors.

- Plee, S.L., et al., "Radiation and Smoke from Gas Turbine Flames Part III," Technical Report No. 12349, March 1978.

Combustion efficiency, lean blowoff, smoke, flame radiation and spark ignition characteristics of gas turbine type flames are examined with particular emphasis on effects of alternate and synthetic fuels. Using a semi-empirical modeling technique, combustion efficiency and flame-stabilization results have been linearly correlated for flames in which heterogeneous effects are negligible (light fuels). Modeling parameters include variations in combustor pressure, inlet temperature, geometry, air flow rate and reference velocity. This technique, which has proven successful in correlating combustion efficiency data from helicopter and automotive gas turbines, should also be applicable to the Army AGT-1500 engine for the XM-1 Main Battle Tank.

- Prado, G.P., "Soot and Hydrocarbon Formation in a Turbulent Diffusion Flame." Sixteenth (International) Symposium on Combustion, Aug 1976 p.649 The Combustion Institute.

Formation and emission of soot and polycyclic aromatic hydrocarbon (PCAH) from a turbulent continuous flow combustor have been studied. Measurements included mass concentration of both soot and PCAH, composition of individual PCAH, and size distribution of soot particles, as a function of mixing intensity, fuel equivalence ratio and type of fuel (kerosene or benzene). Both soot and PCAH concentrations reach maxima early in the flame, after which PCAH decays rapidly and soot decays much slower. The maximum PCAH concentration always preceded that of soot in agreement with the concept that certain PCAH may serve as intermediates in soot formation. An approximate calculation based on the assumptions of local equilibrium with respect to soot formation and a Gaussian distribution of air-fuel mixedness gave satisfactory correlations of the data on soot formation at the higher cold gas velocity. At the lower velocity, the amount of soot and PCAH formed was drastically increased and strongly dependent on fuel atomization.

1 Quigg, H.T., "Effect of Prevaporized JP-5 Fuel on Combustor Performance," Final Report, Naval Air Systems Command Contract N00019-71-C-0486, Phillips Petroleum Co. Res. and Dev. Report 6413-72, 1972.

An experimental investigation was conducted, using the Phillips 2-inch combustor operated under conditions simulating those in modern aircraft turbine engines, to determine effects of differences in JP fuels on flame radiance and exhaust emissions of nitrogen oxides, carbon monoxide, unburned hydrocarbon and soot. Kerosine-type fuels spanning the range in molecular structure (normal paraffins, isoparaffins, cycloparaffins, and aromatics) were evaluated. In initial studies the fuels were prevaporized to minimize effects of differences in their physical properties.

With the combustor and operating conditions used, unburned hydrocarbons in the exhaust were negligible. Empirical equations were developed for each of the five responses with the response expressed as a function of combustor pressure, inlet-air temperature, inlet-air humidity and fuels. NO_x , NO and CO emissions are essentially unchanged with changes in fuels.

The presence of a relatively large concentration of fuel nitrogen (193 ppm) increased total NO_x emissions only slightly at low temperature and not significantly at higher temperatures indicating this level of fuel nitrogen to be a negligible source of NO_x .

2 Roberts, R., Peduzzi, A., and Vitti, G.E., "Experimental Clean Combustor Program, Phase II, Alternate Fuels Addendum," NASA CR-134970, July 1976.

An Alternate Fuels investigation was conducted as an addendum to Phase II of the NASA Experimental Clean Combustor Program. The objective was to experimentally determine the impacts if any, on exhaust emissions, performance, and durability characteristics of the Hybrid and Vorbix low-pollution combustor concepts when operated on test fuels which simulate composition and property changes which might result from future broadened aviation turbine fuel specifications or use of synthetically derived crude feedstocks. Results of the program indicate a significant increase in CO and small NO_x increase in emissions at idle for both combustor concepts, and an increase in THC for the Vorbix concept. Minimal impact was observed on gaseous emissions at high power.

2 Robertson, D.J., Elwood, J.H., and Groth, R.H. "Chemical Composition of Exhaust Particulates From Gas Turbine Engines," Report EPA-600/2-79-041, 1979.

The principal objective of the study was to determine the amount of polycyclic organic compounds and nitrosamines absorbed into the particulate matter. As a part of these tests, two fuels which were identical except for sulfur content were tested - one contained 0.00655% S and other 0.25% S. Sulfur oxides measured by wet chemical techniques showed that a good material balance was obtained between fuel bound sulfur and the SO_2/SO_3 in the exhaust gases.

2 Semerjian, H., and Vranos, A., " NO_x Formation in Premixed Turbulent Flames," Proceedings of Sixteenth (International) Symposium on Combustion," Aug 1976, p. 1481, The Combustion Institute.

NO_x formation has been studied in lean, premixed, turbulent flames stabilized by perforated plates. The burner pressure was atmospheric, but other parameters were representative of gas turbine operating conditions. Pre-vaporized Jet A fuel was injected into preheated unvitiated air and thoroughly mixed prior to combustion. Mixture inlet temperature was 750°K and total residence times were approximately 4 msec. NO_x , CO, CO_2 and hydrocarbon levels were measured along the jet and recirculation zone axes. Results show a very rapid increase in NO_x in the reaction zone which cannot be accounted for by O-atom radical overshoot. Post-flame zone NO_x formation rates agree with the predictions of equilibrium theory. The relative contribution of "prompt NO_x " to the final NO_x levels increases with decreasing equivalence ratio. The rate of NO_x formation in the reaction zone is found to be higher than in laminar flames. Turbulent transport processes are believed to be the dominant effect. NO_x formation via nitrous oxide intermediate does not appear to be important under the present experimental conditions. Large amplitude temperature oscillations observed in turbulent premixed flames were found not to affect NO_x formation rates.

1 Solash, J., Nowack, C.J., and Delfosse, R.J., "Evaluation of a JP-5 Type Fuel Derived From Oil Shale," Report NAPTC-PE-82, May 1976.

A kerosene fuel derived from oil shale was evaluated for suitability as a substitute for petroleum derived JP-5. Engine performance and gaseous emissions were evaluated using a T63-A-5A engine. Specification analyses were performed to determine conformance with the MIL-T-5624J specification for JP-5 grade fuel. Engine performance of the oil shale derived fuel was equivalent to that of a typical petroleum derived JP-5. While carbon monoxide (CO) and unburned hydrocarbon (THC) emissions of the oil shale fuel were equivalent to those of petroleum fuels, the nitrogen oxides (NO_x) were higher for the oil shale fuel. A high concentration of fuel bound nitrogen was implicated as the cause for the high NO_x emissions.

2 Stettler, R.J., and Hardin, M.C., "Initial Evaluation of Coal Derived Liquid Fuels in a Low Emission and Conventional Turbine Combustor," Combustion Institute Central States Section Spring Meeting April 1976.

The combustion performance of three coal derived fuels was examined in both a regenerative low emission automotive turbine engine combustor and a nonregenerative conventional aircraft combustor. The three fuels were a UTAH light fraction, a blend of 20% Utah light and 80% UTAH heavy simulating a full range product and a topped full range product of UTAH and Illinois #6 coal. The low emission combustor was operated in both a low emission mode and a mode simulating the conventional turbine combustor. In both modes of operation, high oxides of nitrogen were recorded with coal base fuels. An analysis of the fuel bound nitrogen indicates that this nitrogen may have contributed heavily to the high oxides of nitrogen in the combustor exhaust. The aircraft conventional combustion system was operated over the full power range. The combustor operation on the coal derived fuels compared to aircraft petroleum derived fuels indicated increased smoking believed due to increased aromatic content and also increased oxides of nitrogen.

Streets, W.L., "Characteristics of Flame Radiation of High Temperature Hydrocarbon Fuels," Phillips Petroleum Co. Research Division Report 2307-59R, Feature No. 6024, April 1959.

Investigation of the effects of a monocyclic and several polycyclic hydroaromatic high temperature hydrocarbon fuels on flame radiation and flame tube metal durability has been conducted in a two-inch laboratory scale combustor under simulated conditions of sea-level takeoff, medium altitude cruising and high altitude loitering flight. Isoparaffinic and aromatic fuels were also included for reference purposes. Supplementary data obtained include deposition, smokiness, combustion efficiency, flame radiation in the Phillips Microburner and ASTM smoke point.

Troth, D.L., "Low-Emissions Combustor Demonstration," USAAMRDL-TR-76-29, (DDA EDR 8723), March 1977.

The objectives of this eighteen-month program were to further develop two low-emission combustors - the prechamber combustor and the modified conventional combustor - which had previously demonstrated low emissions in USAAMRDL Contract DAAJ02-72-C-0005, to install them in a Detroit Diesel Allison Model 250-C20B engine, and to evaluate their performance in an engine environment. The combustors were to retain the 50% overall reduction in gas turbine mass emissions ($\text{CO} + \text{CH}_x + \text{NO}_x$) with no increase in any individual pollutant when tested over a typical Army light observation helicopter (LOH) duty cycle.

In Task I, the prechamber and the modified conventional low-emission combustors were concurrently developed in a series of combustor rig tests to improve their exhaust temperature profiles, durability, stability, ignition characteristics, and pressure losses, while maintaining their emissions abatement and low-smoke characteristics.

Task II documented the baseline combustor performance and Task III evaluated each low-emissions combustor developed in Task I on a DDA Model 250-C20Bd turboshaft gas turbine engine. The prechamber combustor was tested for exhaust temperature profile, cyclic durability, and exhaust emissions on JP-4, JP-5, and on oil shale fuel refined toward a JP-5/Jet-A specification. The modified conventional combustor was engine tested to assess exhaust temperature profile and exhaust emissions from JP-4 fuel.

In Task IV, data reductions and analyses were carried out and combustor rig and engine performance with combustors were correlated, and the effects of the low-emissions combustors on engine performance were determined.

Both low-emission concepts demonstrated significant reductions in exhaust emissions when compared with the base-line combustor, although neither combustor completely met all of the emissions goals. Combustor exhaust temperature profile and liner durability were adequate, causing no engine damage or liner failures after more than 92 engine test hours covering the full range of engine operation.

Tuttle, J.H., et al., "Characteristic Times for Combustion and Pollutant Formation in Spray Combustion," p. 209-219, Sixteenth (International) Symposium on Combustion, The Combustion Institute, (1977).

The dominant physical processes in a liquid spray fueled burner (fuel evaporation, turbulent mixing, and chemical reaction) are characterized by time scales which typify the importance of each process. Guided by a physical model of the flame structure in the wake of a disc with liquid fuel injected into the wake region from the center of the disc, the developed characteristic times are combined to form burner output correlating parameters. The success of these parameters is demonstrated by the correlation of both carbon monoxide and oxides of nitrogen exhaust emissions from the disc burner for various geometries, a wide range of burner operating conditions, and two different fuels. In addition since carbon monoxide and oxides of nitrogen emissions originate primarily in separate regions of the flame, analysis of the characteristic times reveals a means of optimizing the burner geometry to minimize pollutant emissions.

² Tuttle, J.R., Colket, M.B., and Mellor, A.M., "Characteristic Aircraft Type Flames," PURDU-CL-76-05, May, 1976. (EPA R-802650-02).

The overall combustion process occurring within a liquid spray fueled burner is analyzed in terms of the ongoing dominant subprocesses, with particular emphasis on those subprocesses deemed most critical to pollutant emissions. Liquid fuel evaporation, turbulent mixing, and chemical reaction are each considered separately and are characterized by time scales which typify the importance of each subprocess. An axisymmetric burner consisting of a flame stabilized in the wake of a disc with a liquid fuel spray injected into the wake region from the center of the disc is considered experimentally. The basic flame structure behind the disc is composed of a hollow reaction region (shear layer) along the boundary between the recirculation zone and the free stream. Guided by the model of the flame structure, the developed characteristic times are combined to form burner output correlating parameters. The success of these parameters is demonstrated by the correlation of both carbon monoxide and oxides of nitrogen exhaust emissions from the disc burner for various geometries, a wide range of burner operating conditions, and two non-similar fuels. The developed characteristic time model is extended to a conventional gas turbine combustor, GT-309. The model predicts the effect of changes in both combustor inlet conditions and combustor geometry on exhaust emissions and is used to demonstrate the design of a low NO_x burner of the GT-309 class.

³ Vaught, J.M., "The Effect of Inlet Temperature and Pressure on Industrial Turbine Engine Exhaust Emission, ASME Paper 75-WA/GT-11.

The effect of variation of inlet temperature and pressure on exhaust emissions from an industrial gas turbine was determined experimentally. Testing was done in a controlled environment test cell. In addition to temperature and pressure, the influence of two fuels, JP-5 and DF-2, was evaluated. A data matrix of 81 engine operating points was obtained, from which emissions were correlated with engine inlet conditions using regression analysis techniques. The data are analyzed to show how these inlet variables affect compliance with the EPA exhaust emission standards for aircraft and stationary turbine engines.

- Vogel, R.E., Troth, D.L. and Verdouw, A.J., "Fuel Character Effects on Current, High Pressure Ratio, Can-Type Turbine Combustion Systems," Air Force Aero Propulsion Laboratory Report No. AFAPL-TR-79-2072, Feb 1980.

The effect of limited fuel property variation on the performance of current, high pressure ratio can-type combustors was evaluated. The TF41 turbofan combustor was employed. This combustor has conventional dual-orifice fuel injection and film cooling. The combustion zone is approximately stoichiometric at takeoff. Twelve experimental fuels, including JP-4 and JP-8, were tested. Boiling range, hydrogen content, and aromatic type were varied by blending JP-4 and JP-8 fuel with mineral seal oil and two types of aromatic solvent. Fuel hydrogen content varied from 14.5% to 12%. Performance tests were accomplished at idle, altitude cruise, dash, and takeoff conditions. Sea level and altitude ignition tests were also completed. Fuel fouling and carboning characteristics were established. Combustor operating parameters such as liner temperature, pattern factor, ignition fuel-air ratio, lean blowout fuel-air ratio, and exhaust emissions were correlated to fuel properties. The effect of fuel properties on combustor and turbine hardware durability was assessed analytically.

- Vranos, A., "Feasibility Testing of Micronized Coal-Oil (MICO) Fuel in a Model Gas Turbine Combustor," DOE Report R79-954451-1, May 1979.

A preliminary investigation has been made of the combustion characteristics of micronized coal-oil (MICO) slurry fuel sprays and individual droplets. The bulk of the testing was done in a model combustor for the purpose of characterizing particles in the combustor exhaust. In gas turbine applications, these particles must not agglomerate and must remain smaller than a few microns in order to minimize turbine blade erosion. The model combustor employed a variable swirl burner and was specifically constructed at UTRC for use with alternative fuels. The MICO fuel was supplied by DOE for this study and was 32% by weight Pittsburgh seam coal in diesel fuel.

A promising result from this work is that particle agglomeration does not appear to occur. However, combustion efficiency was lower than expected. Gas and particulate sampling were performed with MICO hybrid fuel over the range of fuel flow 9-11 cc/sec, fuel/air ratio $f/a = 0.06-0.095$. Gas samples showed typically 10% O_2 , 10% CO_2 , less than 0.1% CO , and 100-200 PPM NO_x , and were not a strong function of radial flame position. Combustion efficiency was about 50%. Scanning electron micrographs of particulate samples show the presence of individual, nonagglomerated particles of various characteristics. A variety of molten, devolatilized, porous, swollen and partially burned out coal particles were found. Traces of Fe, Al, S, Cl, K, Cu, and Ti were identified in the samples with an X-ray microprobe. Calculations suggest that, at present conditions, radiation loss from particulates is a significant factor in limiting burnout of coal.

- Wilkes, C., and Russell, R.C., "The Effects of Fuel Bound Nitrogen Concentration and Water Injection on NO_x Emissions from 75-MW Gas Turbine," ASME Paper 78-GT-89, April 1978.

This paper describes an investigation into the effects of fuel bound nitrogen concentration, water injection rate, and operating conditions on NO_x emissions from a 75-MW industrial gas turbine equipped with a currently conventional combustion system. The gas turbine was operated over the normal firing temperature range at two compressor inlet guide vane angles to determine the effect of fuel/air ratio and combustor air mass flow rate on NO_x yield. Number 2 distillate fuel was doped with pyridine to simulate bound nitrogen fuels ranging in nitrogen concentration from 0.01 to 0.55 percent by weight. Water was injected into the combustor primary zone for NO_x control at rates depending upon the firing temperature and combustor air mass flow rate. The results of over 130 test points are presented which show the effects of bound nitrogen concentration and water injection rate on the yield of NO_x . It is concluded that as fuel bound nitrogen concentration increases, the effectiveness of water injection in suppressing NO_x emissions decreases due to the change in NO_x yield and the increase in fuel flow rate. For fuels containing high levels of bound nitrogen, such as those derived from coal, it is anticipated that non-conventional combustion systems will be required if some of the current NO_x codes are to be met.

SECTION IV

Flame Ignition and Stability, Reaction Rates, and Spray Characteristics

Atomization of the fuel spray depends on viscosity, surface tension, and density of the fuel and the properties of the injector. Correlations have been developed for particular injectors to predict drop size as a function of fuel properties. Ignition depends on fuel spray drop size and volatility. Volatility for ignition purposes is usually taken as the ASTM 10% evaporation temperature rather than the vapor pressure. Ignition characteristics of alternative fuels may present more problems than burning quality. Fuel properties that affect ignition also control stabilization phenomena.

- Affens, W.A., McLaren, G.W., and Hazlett, R.N., "Flammability and Ignition Properties of JP-5 Jet Fuel From Alternate Sources," NRL Memorandum Report 3191, Dec. 1975.

The flammability and ignition properties of JP-5 from alternate sources were studied. The samples which were investigated included one derived from tar sands, one from shale oil, and five from coal. The tar sand, shale-oil, and one of the coal samples had flash points which were below that of the 140°F specification requirement. The remaining fuels from coal had flash points which were higher than specification requirements, and also higher than those of the usual run of petroleum JP-5. Flammability indices and flammability index-temperature relationships of the alternate fuels were found to differ somewhat from that of the petroleum fuels. Autoignition temperatures of the alternate fuels were similar to that of petroleum-derived fuels. In general, the flammability properties of the JP-5 from alternate sources were not significantly different from that of JP-5 from petroleum.

- Ballal, D.R., and Lefebvre, A.H., "Combustion Efficiency of Gas Turbine Combustors Burning Alternative Fuels," AIAA/SAE 14th Joint Propulsion Conference, Las Vegas, Nev., July 25-27, 1978, AIAA Paper No. 78-1000.

Equations for predicting and correlating the combustion efficiencies of gas turbine combustors are derived for conditions where the heat release is limited either by chemical reaction, mixing or evaporation, or by a combination of reaction and evaporation. Methods for calculating the critical mean drop size, D (crit), above which evaporation becomes the rate-controlling step are presented. It is shown that D (crit) increases with increase in combustion volume, combustion pressure, liner pressure drop and fuel volatility, and diminishes with increase in gas velocity. It is also shown that the ignition energy requirements of liquid hydrocarbon fuels are influenced mainly by their viscosity and volatility, which together govern the rate of fuel evaporation in the ignition zone.

- Ballal, D.R., and Lefebvre, A.H., "Ignition and Flame Quenching of Flowing Heterogeneous Fuel/Air Mixtures," *Combust Flame*, 35, 155 (1979).

A model for combustion in which evaporation is the rate controlling step is developed. The kinetics and mixing are assumed to be infinitely fast compared to evaporation. The model predicts minimum ignition energy for fuels of different volatility and viscosity (drop size) over a range of conditions. At high turbulence levels the experimental values diverge from the predicted ones. Experiments were conducted with iso-octane, diesel oil, and heavy fuel oil.

- Ballal, D.R., and Lefebvre, A.H., "Ignition and Flame Quenching of Quiescent Fuel Mists," Proc. Royal Soc. London, 364(A), 277 (1978).

Quiescent ignition data were obtained for iso-octane, diesel oil, and heavy fuel oil. The minimum ignition energy is shown to be a strong function of drop size (SMD), which is dependent on the fuel viscosity, and the volatility of the fuel, and follows the predicted values from the empirical model well.

- Ballal, D.R., and Lefebvre, A.H., "A General Model of Spark Ignition for Gaseous and Liquid Fuel-Air Mixtures," proceedings of the 18th Symposium (International) on Combustion, p. 1739, the Combustion Institute (1981).

In a previous publication a model for the spark ignition of heterogeneous fuel-air mixtures is described which assumes that chemical reaction rates are infinitely fast, and that the sole criterion for successful ignition is an adequate concentration of fuel vapor in the ignition zone. In the present study this model is extended to include (1) the effects of finite chemical reaction rates, which are known to be significant for well-atomized fuels at low pressures and low equivalence ratios, and (2) the presence of fuel vapor in the mixture flowing into the ignition zone. Thus, it now has general application to both quiescent and flowing mixtures of air with either gaseous, liquid or evaporated fuel, or any combination of these fuels.

The general validity of the new model is demonstrated by a close level of agreement between theoretical predictions of minimum ignition energy and the corresponding experimental values obtained over wide ranges of pressure, velocity, equivalence ratio, mean fuel drop size and fuel volatility.

- Clark, J.A., et al., "Radiation/Smoke and Combustion Efficiency from Gas Turbine Flames, IV. Fuel Property Effects on Performance," PURDU-CL-79-05, March 1979. (USATARADCOM DAAE07-76-C-0063, Technical Report No. 12438).

The performance of gas turbine combustors with respect to combustion efficiency, flame stabilization, ignition, smoke and radiation, burning a wide range of fuel types is considered. The experimental portion of the program was conducted with a simplified combustor designed to yield apparatus independent results. Employing the characteristic time approach a flame stabilization model is used to predict lean stability limits for previous and future experiments. In addition, an ignition model is derived from the flame stabilization work and used to correlate ignition data available in the literature.

- Clark, J.A., et al., "Radiation/Smoke and Combustion Efficiency from Gas Turbine Flames. Part V. Fuel Property Effects on Performance," USATARADCOM Tech. Rep. No. 12487. (1980).

Gas turbine combustor lean blowoff, ignition, and efficiency are studied, stressing the effects of burning alternative fuels. The experimental program uses a simplified model combustor to obtain results which are not configuration specific. Semi-empirical models derived from these results are then used to predict some performance aspects of the AGT-1500 combustor, which is used in the engine of the latest Army Main Battle Tank. The lean blowoff model, formerly applied only to relatively light fuels, is shown also to be valid for JP-10, unleaded gasoline, number 4 oil and number 6 oil. The ignition model has been extended to include the effect of kinetics, and now deals more completely with flowing as well as quiescent fuel-air mixtures. The combustion efficiency model demonstrates that AGT-1500 combustion efficiency is mixing-controlled, even for fuels as heavy as DF-2.

- Clarke, A.E., et al., "Combustion Processes in a Spherical Combustor," Tenth Symposium (International) on Combustion, the Combustion Institute, 1965, p. 1151-1166.

The object of this work was to obtain a better understanding of the combustion processes in a spherical combustor, with the specific aim of determining the maximum loading for the propane/oxygen system.

Details are given of a series of experiments in which various fuel (hydrocarbons and hydrogen) oxygen/nitrogen mixtures were burned in different sizes of spherical combustors over ranges of equivalence ratio, pressure, injector pressure loss, and external heat loss. The reduction in injector pressure loss from 50% to 5% at $\phi = 1.0$ and from 40% to 1% at $\phi = 0.6$ had little effect on the stability performance.

The reaction pressure exponent of propane/oxygen/nitrogen mixtures was found to be 2 and it was shown that nitrogen could be regarded as equivalent to an external heat loss. The blow-out data obtained were correlated by means of a semiempirical reaction equation based upon a mass balance which assumed that fuel was the only unburned product.

The experimental blow-out data were also correlated against burning velocity at 300°K inlet temperature - this correlation being described by the equation

$$(N/VP^2)_{\max} = 0.1Su^{1.75}.$$

Attempts were then made to predict the peak loading for a propane/oxygen mixture using (a) the derived semiempirical equation and (b) extrapolation of the burning velocity correlation and general practical data. The former gave a value of some 7100 gmole/sec 1 atm² and the latter some 2900 gmole/sec 1 atm². Attempts to explain this discrepancy have so far failed unless it is assumed that reaction order and/or activation energy varies with composition or that the mixing processes assume control at the very high throughputs in the sphere.

- Clayton, R.M., "A Partial Oxidation Staging Concept for Gas Turbine Using Broadened Specification Fuels," ASME Paper No. 79-GT-169, March 1979.

A concept is described for using a very fuel-rich partial oxidation process as the first stage of a two-stage combustion system for onboard processing of broadened specification fuels to improve their combustion characteristics. Results of an initial step in the experimental verification of the concept are presented, where the basic benefits of H_2 enrichment are shown to provide extended lean-combustion limits and permit simultaneous achievement of ultralow levels of NO_x , CO, and HC emissions. The H_2 required to obtain these results is within the range available from a partial oxidation precombustion stage. Operation of a catalytic partial oxidation reactor using a conventional aviation turbine fuel (JP-5) and an unconventional fuel (blend of JP5/xylene) is shown to produce a "fuel gas" stream with near-theoretical equilibrium H_2 content. However, a number of design considerations indicate that the precombustion stage should be incorporated as a thermal reaction.

- Colket, M.B., et al., "Radiation and Smoke from Gas Turbine Flames, Part II: Fuel Effects on Performance," PURDU-CL-77-01, 1977, (USATACOM DAAE07-76-C-0063).

Fuel effects upon gas turbine combustor performance, including combustion efficiency, lean blow off, smoke, and flame radiation, must be defined to minimize developmental efforts in adapting existing Army engines to synthetic and alternate fuels. Limited results for efficiency, blow off, and smoke concentrations are presented for a simulated combustor primary zone burning various fuels, and correlating schemes capable of collapsing the data for blow off and efficiency are refined. Preliminary flame radiation measurements have been obtained. Future tests required on all of the above performance parameters, as well as on spark ignition are suggested.

- Detroit Diesel Allison, "Model 501-K17 Gas Turbine Single Burner Evaluation of Shale Derived Marine Diesel Fuel," DDA EDR 8660, 31 Jan 1976.

A significant quantity of crude oil has been extracted from Colorado oil shale in the Paraho project. This crude was subsequently experimentally refined to produce a broad range of military fuels. This report presents results obtained in gas turbine combustion tests of a marine diesel fuel from this project. A can-annular segment of the DDA 501-K17 marine gas turbine engine was used in the tests. Burner conditions simulated the operating spectrum experienced by this engine in the U.S. Navy DD963 class destroyers. Starting and steady state points from zero to full power were examined. The performance of the shale fuel was compared with that obtained at equivalent conditions with a petroleum marine diesel fuel from the U.S. Navy supplies.

The starting characteristics and combustion efficiencies obtained with the shale derived fuel were acceptable, and within the performance range expected for petroleum fuels to DOD Specification MIL-F-16884-G. No tendencies toward increased carbon deposition or liner wall temperature elevation were indicated in these limited duration tests.

2. Dodd, W.J., Renie, J.P., and Mellor, A.M., "Gas Turbine Engine Stability and Performance as Determined by Fuel and Injector Type," USATACOM Report No. 12065, Purdue Report No. PURDU-CL-75-05, 1975.

In order to establish the versatility of the gas turbine combustor in utilizing non-specification fuels such as those expected to be derived from refinement of oil shale and liquefaction of coal, an experimental program has been initiated to determine the effects of fuel and injector type on the spray combustion process. The initial phase of this program is an exploratory study of combustion efficiency and stability for two fuels, Jet A and #5 fuel oil, injected through two different pressure atomizing nozzles.

Data correlation techniques including both the use of traditional correlating parameters and characteristic time model of the spray combustion process are discussed and compared. Using these correlating parameters, combustion efficiency and stability data taken Jet A fuel and #5 fuel oil in the laboratory combustor are compared with similar data taken in a T-63 combustor (Moses, 1975), showing applicability of simplified test combustor data to actual combustors. Data for Jet A fuel injected through two different nozzles indicates that both stability and efficiency are adversely affected by increased droplet lifetime; however further increasing calculated droplet lifetime by the use of #5 fuel oil produced no further decrease in measured combustion efficiency and resulted in improved stability at the lean limit. Several explanations for these results are examined, with emphasis on possible measurement errors and changes in physical phenomena which may occur in the evaporation of large droplets.

2. Foster, H.H. "Ignition-Energy Requirements in a Single Tubular Combustor," NACA Report RM-E51A24 Washington, March 1951.

An investigation was conducted to determine the minimum spark energy required from ignition in a single tubular combustor. Data were obtained at simulated static sea-level engine starting conditions for a wide range of ambient temperatures, and also for a range of altitude inlet-air pressures and air-flow rates. The inlet-air pressure and flow rates limiting ignition are compared with those limiting steady-state burning in the combustor. Three different fuels were used to indicate the effect of fuel volatility on ignition.

A decrease in ambient temperature from 70° to -60° F at sea-level engine-cranking conditions required an increase in spark energy from 0.022 to about 1.5 joules for ignition in the combustor with the least volatile fuel investigated; comparable trends were obtained with more volatile fuels. The altitude ignition limits were extended by increasing the spark energy above that of the conventional system. A spark energy of approximately 10 joules per spark at a sparking rate of 8 per second gave satisfactory ignition at combustor-inlet conditions close to the steady-state burning limits of the combustor at low and intermediate air-flow rates. The ignition-energy requirements at both sea-level and altitude combustor-inlet conditions generally decreased with an increase in fuel volatility.

- Foster, H.H., and Straight, D.M., "Effect of Fuel Volatility Characteristics on Ignition Energy Requirements in a Turbojet Combustor," NACA RM E52J21, (1953).

Six fuels were tested for ignition characteristics in a J-33 combustor. The minimum ignition energy correlated with the ASTM 10% evaporated fuel temperature but not the Reid vapor pressure.

- Gleason C.C., and Bahr, D.W., "Alternate Fuels Addendum, Phase II. Experimental Clean Combustor Program," NASA CR-134972, January 1976.

A study was conducted to investigate the characteristics of current and advanced low-emissions combustors when operated with special test fuels simulating broader ranges of combustion properties of petroleum or coal-derived fuels. Five fuels were evaluated; conventional JP-5, conventional No. 2 Diesel, two different blends of Jet A and commercial aromatic mixtures - "zylene bottoms" and "naphthalene charge stock", and a fuel derived from shale oil crude which was refined to Jet A specifications. Three CF6-50 engine size combustor types were evaluated; the standard production combustor, a Radial/Axial Staged Combustor, and a Double Annular Combustor. Altitude relight characteristics were evaluated in a 60° sector combustor rig.

- Gleason, C.C., et. al., "Evaluation of Fuel Character Effects on the J79 Engine Combustion System," AFAPL-TR-79-2015, June 1979.

Results of a program to determine the effects of broad variations in fuel properties on the performance, emissions, and durability of the J79-17A turbojet engine combustion system are presented. Combustor tests conducted at engine idle, takeoff, subsonic cruise, supersonic dash, cold day ground start, and altitude relight operating conditions with 13 different fuels are described. The test fuels covered a range of hydrogen contents (12.0 to 14.5 percent), aromatic type (monocyclic and bicyclic), initial boiling point (285 to 393 K), final boiling point (552 to 679 K) and viscosity (0.83 to 3.25 mm²/s at 300 K).

At cold day ground start conditions (to 329 K) lightoff was obtained with all fuels, but the required fuel-air ratio increased with the more viscous fuels.

At altitude conditions, the current engine relight limits with JP-4/JP-5 fuel were essentially met or exceeded with all of the JP-4 or JP-8 based fuel blends. However, a very significant reduction in altitude relight capability was found when a No. 2 diesel fuel was tested.

- Gleason, C.C., et al, "Evaluation of Fuel Character Effects on F101 Engine Combustion System, Final Report," USAF Contract F33615-77-C-2043, AFAPL-TR-79-2018, June 1979.

Results of a program to determine the effects of broad variations in fuel properties on the performance, emissions and durability of the General Electric F101 augmented turbofan engine main combustion system are presented. Combustor rig tests conducted at engine idle, takeoff, cruise, dash, cold day ground start and altitude relight operating conditions with

13 different fuels are described. The test fuels covered a range of hydrogen contents (12.0 to 14.5%), aromatic type (monocyclic and bicyclic), initial boiling point (285 to 393 K), final boiling point (552 to 679 K) and viscosity (0.83 to 3.25 mm²/s at 300 K).

Cold day ground start and altitude relight correlated with fuel atomization/volatility parameters, but showed no dependence on hydrogen content.

- Henein, N.A., and Bolt, J.A., "Kinetic Considerations in the Autoignition and Combustion of Fuel Sprays in Swirling Air," ASME Paper No. 72-DGP-8, 1972.

The kinetics of the physical and chemical preignition processes are studied for fuel sprays injected in high-speed diesel engines. The chemical reactions are found to be the rate controlling processes. The present and many previous experimental results support this conclusion. The overall preignition reactions follow an Arrhenius-type relationship with temperature. The global activation energy is calculated for three fuels: diesel No. 2, CITE (Compression Ignition Turbine Engine fuel), and gasoline. The global activation energy decreases with increase in the cetane number of the fuel. The rate of heat release reveals two types of reactions for both diesel No. 2, and CITE fuels. A slow reaction starts near the end of the ignition delay and is followed by a fast reaction. These two reactions are also observed when a barium antismoke compound is added to the diesel fuel. The barium additive does not affect the length of the ignition delay, but accelerates the main combustion reactions.

- Horstman, W.W., and Jackson, J.L., "Combustion Characteristics of Special Hydrocarbon Jet Fuel," ASD TDR-62-682 WPAFB, 1962.

A single combustor from a General Electric J-79 engine was used to evaluate combustion efficiency, flame radiation, fuel consumption, and altitude relight characteristics of twelve hydrocarbon fuels. Selection of fuels was based primarily on heat of combustion, density, Luminometer Number, and thermal stability for potential use in supersonic aircraft gas turbine engines. Tests were made with simulated Mach 1.5, 2, 2.5, and 3 speeds at 80,000 feet altitude, and a higher combustor severity condition at the maximum compressor output.

Ease of relight at simulated altitude conditions increased with decreasing ASTM 10% distillation temperature and with increasing paraffin content of the fuel.

- Hunter, S.C., et al., "Advanced, Small, High-Temperature-Rise Combustor Program," Final Report, Volume I, USAAMRDL Tech Report 74-3A.

This report describes an analytical and experimental study of advanced, small, high-temperature combustors. The objectives of the 32-month program were

a) To develop and validate an analytical design technique for small, high-temperature-rise, low-airflow combustors and related components

b) To define the limitations associated with these small combustors and related components and the effects of these limitations on the cycle and the configuration of advanced-technology engines

Analytical models were developed to predict the characteristics and performance of the basic combustor elements, including fuel injection, primary zone, dilution zone, and liner cooling. Nine combustor element rig test programs were conducted to provide data to update and validate the analytical models. Based on the analysis and rig test results, a full-scale combustor was designed, fabricated, and tested. An ancillary material screening program was conducted to select the most suitable existing material for combustor application. A relatively new material (IN-586) was selected. Material-property tests were conducted to supplement published data for this material.

The analytical models were used to assess combustor design and performance limitations and the applicability of the design techniques over an airflow range of 2 to 5 pounds per second, cycle pressure ratio range of 10 to 16 (including recuperation), and a turbine inlet temperature range of 2300 °F to 2700 °F.

Multifuel capability was examined including MIL-T-5424, Grades JP-4 and JP-5, MIL-T-83133, Grade JP-8, and Aviation Turbine Fuel, ASTM D1655-67 Type A-1.

- Ingebo, R.D., and Norgren, C.T., "Combustor Exhaust Emissions with Air-Atomizing Splash-Groove Fuel Injectors Burning Jet A and Diesel Number 2 Fuel," NASA TMX-3255, July 1975.

Air-atomizing splash-groove injectors, utilizing fuel jets impinging against a grooved face, gave improved primary-zone fuel spreading and reduced combustor exhaust emissions for Jet A and diesel number 2 fuels. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air pressures of 41 to 203 N/cm², inlet-air temperatures of 477 to 811 K, and a reference velocity of 21.3 m/sec. Combustor blowout limits were similar for diesel number 2 and Jet A fuels.

- Ingebo, R.D., Norgren, C.T., "Combustor Exhaust Emissions and Blowout Limits with Diesel Number 2 and Jet A Fuels Utilizing Air-Atomizing and Pressure Atomizing Nozzles," NASA-TM-X-71803; E-8483. Presented at Western States Section of the Combustion Institute, Palo Alto, California Oct 1975.

Experimental tests with diesel number 2 and Jet A fuels were conducted in a combustor segment to obtain comparative data on exhaust emissions and blowout limits. An air-atomizing nozzle was used to inject the fuels. Tests were also made with diesel number 2 fuel using a pressure-atomizing nozzle to determine the effectiveness of the air-atomizing nozzle in reducing exhaust emissions. Test conditions included fuel-air ratios of 0.008 to 0.018, inlet-air total pressures and temperatures of 41 to 203 newtons per square centimeter and 477 to 811 K, respectively, and a reference velocity of 21.3 meters per second. Blowout limits were approximately the same for the two fuels.

- Jasuja, A.K., "Atomization of Crude and Residual Fuel Oils," ASME Paper No. 78-GT-83, Gas Turbine Conference, London, England, April 1978.

A study is made of the effects that fuel properties have upon the mean droplet size characteristics of three fuel atomizer types that are commonly employed in the gas turbine engine. The fuels tested included kerosine, gas oil, and a heavy residual fuel oil, and each was passed through a pressure swirl jet, a prefilming airblast, and a plain-jet airblast atomizer in turn. Tests were carried out at pressure levels close to ambient and mean drop sizes were determined using a light-scattering technique. Two main points emerge from the results: Firstly, for all atomizers tested, that the existing drop-size correlations are not sufficiently accurate for use with the high-viscosity residual fuel oils. Secondly, that the fuel drop-size decreases with the change in atomizer type from plain-jet airblast to prefilming airblast. The difference in performance of the two types of airblast atomizers is most noticeable for the residual fuel oil, particularly so at pressure drop levels of less than around five percent. Use is also made of the many data points collected to derive improved drop-size correlations which may be used over the whole range of fuels tested.

4 Lefebvre, A.H., Mellor, A.M., and Peters, J.E., "Ignition/Stabilization/Atomization: Alternative Fuels in Gas Turbine Combustors," in Alternative Hydrocarbon Fuels: Combustion and Chemical Kinetics, Edited by Craig T. Bowman and Jorgen Birkeland, Vol. 62, of Progress in Astronautics and Aeronautics, American Institute of Aeronautics and Astronautics, Inc., 1978, p. 137.

It is pointed out that fuel preparation, ignition, flame spreading, and flame stabilization are important considerations in the design of gas turbine engines. It is discussed how changes in the major properties of alternative fuels will affect atomization, ignition, flame spread, and lean blowoff in gas turbine burners. It is found that it is primarily the physical properties of the fuel which influence the performance parameters. Studies have shown that ignition is strongly dependent on fuel volatility and viscosity. A graph showing the influence of atomization quality on ignition limits is presented. For all fuels considered the atomization quality on ignition limits is presented. For all fuels considered the atomization quality is found to be markedly inferior to that of normal kerosine, indicating that problems of ignition and lean blowoff will be more severe. The correlations predict that jet fuels derived from shale oils, tar sands, and coal syncrudes will pose more serious problems of atomization than similar petroleum-based fuels.

4 Leonard, P.A., and Mellor, A.M., "Lean Blowoff in High Intensity Combustion with Dominant Fuel Spray Effects," to be published in Combust Flame (1980).

The characteristic time model for lean blowoff (Plee and Mellor, 1979) has been used to predict extinction of disc-stabilized flames of No. 4 and No. 6 oils, unleaded gasoline and JP-10. The predictions show good agreement with experimental values of blowoff equivalence ratio obtained at pressures of 2-6 atm, inlet air temperatures of 500-800 K and 1.5 Kg/sec

air mass flow. Droplets penetrating the shear layer strongly augment the stabilization process at lower combustor loadings, especially with No. 6 oil. In addition, the characteristic time model is used to correlate blowoff in AVCO-Lycoming AGT-1500 combustors under starting and idle conditions. Droplet effects are indicated to be significant for No. 6 oil and for certain low-smoke combustor designs.

- Marchionna, N., and Opdyke, G., Jr., "Turbine Fuel Tolerance Study, Phase II," USATACOM Tech. Rep. No. 12191. (1976)

The ignition performance of JP-5, #4 and #5 residual fuel oils was examined in an AGT 1500 gas turbine. The fuel-air ratio required for ignition correlated with both the 10% evaporated fuel temperature and with the viscosity. The fuel-air ratio required for ignition decreased as the viscosity decreased due to better atomization.

- Marchionna, N.R., et.al., "Turbine Fuel Tolerance Study, Initial Engine Test: No. 4 oil," USATARADCOM Technical Report No. 12272, April 1977.

An AGT 1500 vehicular gas turbine engine was operated on No. 4 residual oil using a specially modified combustor. Problem areas encountered included cold starting ignition.

- Marchionna, N., "Turbine Fuel Tolerance Study: Multifuel Engine Tests," USATARADCOM Technical Report 12392 (USATARADCOM DAAE07-74-C-0274), July 1978.

An AGT 1500 vehicular gas turbine engine was tested for multifuel capability. Overall performance did not vary when operating on JP-4, DF-2, or unleaded gasoline. Engine starts were demonstrated with No. 4 oil up to a viscosity of at least 26.5 centistokes at approximately 30°F.

- Moses, C.A., "Studies of Fuel Volatility Effects on Turbine Combustor Performance," 1975 Spring Meeting of Western and Central Sections of Combustion Institute.

An exploratory investigation has been made concerning the effects that the boiling-point-distribution of the fuel can have on turbine-combustor performance, in particular ignition, stability, exhaust emissions, and combustion efficiency. The experiments were conducted in a 5-atmosphere combustor rig based on T-63 engine hardware. Four fuels were used covering the range of viable fuels (JP-4 to #5 fuel oil). Higher vapor pressures were found to improve ignition but a significant difference was found between a "natural" vapor pressure and one that was obtained by blending the fuel with n-pentane.

- Moses, C.A., and Naegeli, D.W., "Fuel Property Effects on Combustor Performance," ASME Paper 79-GT-178, March 1979.

Two combustor rigs have been used to study the sensitivity of combustor performance to the physical and chemical properties of fuels. The purpose was to determine the impact of broadening fuel specifications and using non-specification fuels in emergencies. Nineteen fuels including

synfuels were used to accentuate the properties of concern: composition, viscosity, and boiling point distribution. The combustors were instrumented for flame radiation, liner temperature, and exhaust emissions; testing included ignition, stability, and combustion efficiency.

Stability was about the same for all fuels except that gasoline could be burned leaner at idle conditions. The more volatile fuels could be ignited under leaner conditions.

- Peters, J.E., and Mellor, A.M., "An Ignition Model for Quiescent Fuel Sprays," *Combust Flame*, 38, 65 (1980).

An evaporation controlled ignition model is developed on the basis of data in the literature which suggest that two fuel properties which affect evaporation, volatility and viscosity, also strongly influence ignition. Due to the similarities between flame stabilization and ignition the model follows from an existing flame stabilization theory. Basically, the model employs a characteristic time approach which associates specific times with the physical processes which occur during ignition and states that the ignition limit is reached when the mixing rate of the spark kernel with its environment equals the fuel evaporation rate. A favorable comparison between the model and ignition data for quiescent fuel and air mixtures is observed.

- Plee, S.L., Schmidt, D.A., and Mellor, A.M., "Flame Efficiency, Stabilization and Performance in Prevaporizing/Premixing Combustors", PURDU-CL-77-07, December 1977. (Air Force Office of Scientific Research AFOSR 76-2936)

Problems of combustion efficiency, incomplete prevaporization and flame stabilization (blowoff and/or flashback) associated with advanced prevaporizing/premixing turbojet combustors, afterburners and ramjet combustors are examined experimentally using a simplified axisymmetric burner. This flameholder configuration retains the same fundamental combustion processes of prevaporizing/premixing combustors while eliminating some of the complexity of the practical hardware. In addition to variations in combustor pressure, inlet temperature, equivalence ratio and air velocity typical of modern combustors, geometry and heterogeneous effects are also considered.

Both flame stabilization and combustion efficiency data are examined using conventional (Lefebvre, 1966) and characteristic time (Mellor, 1976) correlations. Characteristic times, which have already been used to correlate and predict gaseous emissions in conventional combustors, are quantified here for blowoff. The model is based on the flame stabilization theory of Zukoski and Marble (1956) and includes inlet, geometry and heterogeneous effects simultaneously, unlike traditional loading parameters. Combustion efficiency data obtained for this study are not yet included in the correlation. Detailed internal species concentration, temperature and velocity measurements are planned to help identify proper scaling parameters for the combustion efficiency model.

Flame flashback into the fuel preparation tube has not been observed for any of our operating conditions. These results are consistent with a

recent literature review (Plee and Mellor, 1977) which has identified important mechanisms of upstream flame propagation. This study shows that flow disturbances rather than combustor inlet conditions are responsible for the "flashback" reported in non-catalytic combustors.

- Plee, S.L., et al., "Radiation and Smoke from Gas Turbine Flames, Part III," Technical Report No. 12349, March 1978.

Combustion efficiency, lean blowoff, smoke, flame radiation and spark ignition characteristics of gas turbine type flames are examined with particular emphasis on effects of alternate and synthetic fuels. Using a semi-empirical modeling technique, combustion efficiency and flame stabilization results have been linearly correlated for flames in which heterogeneous effects are negligible (light fuels). Modeling parameters include variations in combustor pressure, inlet temperature, geometry, air flow rate and reference velocity. This technique, which has proven successful in correlating combustion efficiency data from helicopter and automotive gas turbines, should also be applicable to the Army AGT-1500 engine for the XM-1 Main Battle Tank.

Decreased volatility and increased viscosity can inhibit fuel ignitability. A model has been developed based on current literature which correlates ignition characteristics with the 10% fuel evaporated temperature for six different fuels. For successful spark ignition, sufficient fuel vapor must be present at the ignition point to exceed the lean flammability limit; thus, increasing fuel volatility and decreasing fuel viscosity improve ignition. A spark ignition test rig will be constructed in an effort to validate this model.

For flame stabilization, the influence of fuel property variations (viscosity and volatility) has been incorporated in the model using characteristic times associated with fuel evaporation and penetration.

- Plee, S.L., and Mellor, A.M., "Flame Stabilization in Simplified Prevaporizing, Partially Vaporizing, and Conventional Gas Turbine Combustors," Journal of Energy, 2, 346, (1978).

Lean blowoff equivalence ratios are presented using conventional correlating parameters for two different axisymmetric flameholder configurations. These simplified geometries model the same fundamental combustion processes of conventional and advanced prevaporizing/premixing gas turbine combustors while eliminating some of the complexity of practical hardware. Combustor pressure, inlet temperature, air velocity, geometry, injector size, and fuel type are varied over ranges typical of gas turbine combustor operation. Results indicate that the flame is predominantly mixing controlled; however, heterogeneous effects associated with fuel variations show that increasing the initial droplet evaporation time (reducing the local fuel concentration) narrows the lean limit, whereas increasing fuel penetration (increasing the length of the stabilization zone) actually enhances flame stabilization.

- Plee, S.L., and Mellor, A.M., "Characteristic Time Correlation for Lean Blowoff of Bluff-Body-Stabilized Flames," Combust Flame, 35, 61, 1979.

Characteristic times associated with turbulent mixing, homogeneous chemical kinetics, liquid-droplet evaporation, and fuel injection are quantified for lean blowoff. The model linearly correlates variations in combustor pressure, inlet temperature, air velocity, flame-holder geometry, fuel type, and injector size using data obtained from three different bluff-body stabilizers that simulate the same fundamental combustion processes of both conventional and advanced prevaporizing-premixing gas-turbine combustors. Lean blowoff is viewed as the competition between a fluid mechanic and chemical time evaluated in the shear-layer region between the hot recirculation zone and the free stream.

~ Rao, K.V.L., and Lefebvre, A.H., "Minimum ignition energies in flowing kerosine-air mixtures," *Combust Flame* 27, 1, (1976).

The effect of spray quality on ignition was examined. The Sauter Mean Diameter decreases with decreasing viscosity, and the smaller drops provide more surface area for evaporation which enhances ignition.

~ Rayle, W.D., and Douglas, H.W., "Investigation of Ignition Characteristics of AN-F-32 and two AN-F-38a Fuels in Single Can-type Turbojet Combustor," NACA RM E50H16a, 1950.

Ignition characteristics were determined for three fuels in a J-33 combustor with an ignition system featuring an air gap plug providing 0.106 - 0.033 joules per spark at a rate of 400-800 sparks per second. The critical fuel flow for ignition correlated best with the 10% evaporated fuel temperature. Thus, the light ends of the fuel are significant in ignition.

~ Rizkalla, A.A., and Lefebvre, A.H., "The Influence of Air and Liquid Properties on Airblast Atomization," *Transactions of the ASME, Journal of Fluids Engineering*, p.316, September 1975.

An experimental study of airblast atomization has been conducted using a specially designed atomizer in which the liquid is first spread into a thin sheet and then exposed on both sides to high-velocity air. The first results of this study, reported in reference (1) were confined to the effects of liquid properties, namely, viscosity, surface tension, and density on atomization quality. Since then the experimental data have been extended to include the influence of air properties, notably temperature and pressure, on mean drop size. The purpose of this paper is to present these data and to show that the effects for both air and liquid properties on atomization quality are described by a dimensionless equation.

~ Roberts, R., Peduzzi, A., and Vitti, G.E., "Experimental Clean Combustor Program, Phase II, Alternate Fuels Addendum," NASA CR-134970, July 1976.

An alternate fuels investigation was conducted as an addendum to Phase II of the NASA Experimental Clean Combustor Program. The objective was to experimentally determine the impacts, if any, on exhaust emissions, performance, and durability characteristics of the Hybrid and Vorbix low-pollution combustor concepts when operated on test fuels which simulate

composition and property changes which might result from future broadened aviation turbine fuel specifications or use of synthetically derived crude feedstocks. Altitude stability was not affected for the Vorbix combustor, but was substantially reduced for the Hybrid concept.

1 Robson, K., "The Influence of Changing Fuel Specification on Combustor Performance and Emissions: A Review of Derby Test Experience," Rolls-Royce Aero Division.

The adoption of denser and more viscous fuels will lead to starting problems both on cold days and at altitude. White smoke on starting is also likely to become a problem over a greater range of ambient temperatures.

2 Spadaccini, L.J., "Autoignition Characteristics of Hydrocarbon Fuels at Elevated Temperatures and Pressures," ASME Paper No. 76-GT-3, published in the Journal of Engineering for Power, p.83, Jan. 1977.

A problem to be treated in the design of prevaporizing/premixing combustors for use in advanced air-breathing engines is autoignition of the fuel-air mixture prior to injection into the primary combustion zone. Measurements of the autoignition characteristics of JP-4, No. 2 fuel oil, and No. 6 fuel oil were made in dry air at temperatures in the range 750°F (400°C) to 1100°F (593°C) and at pressures in the range 100 psia (6.8 atm) to 240 psia (16.3 atm). Tests were performed in a steady-flow apparatus in which the pressure, temperature, and mixture flow rate were adjusted to induce autoignition and maintain a stationary flame front. The ignition delay time was considered equivalent to the residence time for the fuel-air mixture between the point of injection and the axial position of the flame, and it was computed from the average flow velocity. The effects of a number of physical factors, including air pressure and temperature, fuel temperature and concentration, and initial spray characteristics (e.g., droplet size and size distribution), upon the ignition characteristics were evaluated.

3 Vogel, R.E., Troth, D.L., and Verdouw, A.J., "Fuel Character Effects on Current, High Pressure Ratio, Can-Type Turbine Combustion Systems," Air Force Aero Propulsion Laboratory Report No. AFAPL-TR-79-2072, February 1980.

The effect of limited fuel property variation on the performance of current, high pressure ratio can-type combustors was evaluated. The TF41 turbofan combustor was employed. This combustor has conventional dual-orifice fuel injection and film cooling. The combustion zone is approximately stoichiometric at takeoff. Twelve experimental fuels, including JP-4 and JP-8, were tested. Boiling range, hydrogen content, and aromatic type were varied by blending JP-4, and JP-8 fuel with mineral seal oil and two types of aromatic solvents. Fuel hydrogen content varied from 14.5% to 12%. Sea level and altitude ignition tests were completed. Fuel fouling and carboning characteristics were established.

- Weiss, M.A., Lang, R.J., and Longwell, J.P., "Combustion Rates in Spherical Reactors - Effects of Inlet Temperature and Fuel Type," Industrial and Engineering Chemistry, 50, No. 2, February 1958.

An earlier discussion (1) presented data on combustion rates in insulated spherical reactors. A homogeneous mixture of iso-octane (2,2,4-trimethylpentane) and air was injected through a small perforated ball at the center of spherical reactor into a concentric reaction space. Combustion occurred continuously in this reaction space, while the gases were vigorously stirred by the incoming jets. Products of combustion were exhausted through holes in the outer spherical walls of the reaction zone. Because of the vigorous stirring, it was found useful to assume that the reactor was completely stirred - that the time of mixing of fresh material into the reacting gases was small compared to the time of reaction. If this assumption is true, rates of combustion are limited by the chemical kinetics of reaction between fuel and oxygen. Assuming an extremely simple reaction, quasikinetic constants were derived for the iso-octane-air system; the apparent overall activation energy of the reaction was about 42,000 calories. This number was determined by trial as the value best matching the observed blowout data to the blowouts predicted by the simple reaction scheme. The first objective in this present work was to vary the inlet temperature as a check on the earlier activation energy. A second objective was to test fuels other than iso-octane; of interest were both fuel evaluation per se and the attempt to shed light on the combustion mechanism by interpreting the variation of combustion rates with fuel structure.

SECTION V Carbon Deposition

Carbon deposits generally increase with decreasing fuel volatility and increasing degree of fuel unsaturation (more aromatics and olefins). Under some conditions polycyclic aromatics produce more deposits than monocyclic aromatics. Some combustor designs show little effect of fuel properties on carbon deposition.

4 Detroit Diesel Allison, "Model 501-K17 Gas Turbine Single Burner Evaluation of Shale Derived Marine Diesel Fuel," DDA EDR 8660, Jan 1976.

A significant quantity of crude oil has been extracted from Colorado oil shale in the Paraho project. This crude was subsequently experimentally refined to produce a broad range of military fuels. This report presents results obtained in gas turbine combustion tests of a marine diesel fuel from this project. A can-annular segment of the DDA 501-K17 marine gas turbine engine was used in the tests. Burner conditions simulated the operating spectrum experienced by this engine in the U.S. Navy DD963 class destroyers. Starting and steady state points from zero to full power were examined. The performance of the shale fuel was compared with that obtained at equivalent conditions with a petroleum marine diesel fuel from the U.S. Navy supplies.

The starting characteristics and combustion efficiencies obtained with the shale derived fuel were acceptable, and within the performance range expected for petroleum fuel to DOD Specification MIL-F-16884-G. No tendencies toward increased carbon deposition or liner wall temperature elevation were indicated in these limited duration tests. Exhaust smoke was measurably higher with the shale fuel, but deemed no greater than possible with a minimum quantity petroleum fuel to the same specification. The carbon monoxide and unburned hydrocarbon emissions from shale fuel operation were normal. However, the quantity of nitrogen oxides emitted was distinctly larger than obtained from petroleum fuel operation. The sharply increased NO_x is attributed to higher levels of nitrogen bearing compounds present in the shale fuel. Combustor design modifications to materially reduce the liquid fuel nitrogen conversion do not appear hopeful. Refining studies to reduce the nitrogen in the shale fuels are recommended.

4 Ekstedt, E.E., and Macaulay, R.W., "Combustion of Heavy Distillate Fuel for the LM2500 Gas Turbine," ASME 72-GT-24, Jan. 1973.

The combustor for the LM2500 is an annular combustor developed for use with marine and industrial fuels including natural gas and heavy distillates. This paper relates the development of this combustor including some of the design criteria, the fuel properties and some of the combustor performance results such as exit gas temperature patterns, ignition, pressure loss, and efficiency. The engine combustor operates with a clear smokeless stack utilizing heavy distillate fuels and is free of carbon formation. Fuel properties and atomization properties are related to exhaust smoke. Investigations have included a wide range of

fuels and several fuel injector designs. The engine has operated in GTS Adm. Wm. M. Callaghan for a total of more than 10,000 hrs with no combustor problems, smoke, carbon, life or otherwise.

² Gleason, C.C., and Bahr, D.W., "Alternate Fuels Addendum, Phase II. Experimental Clean Combustor Program," NASA CR¹134972, Jan. 1976.

A study was conducted to investigate the characteristics of current and advanced low-emissions combustors when operated with special test fuels simulating broader ranges of combustion properties of petroleum or coal-derived fuels. Five fuels were evaluated; conventional JP-5, conventional No. 2 Diesel, two different blends of Jet A and commercial aromatic mixtures¹ "xylene bottoms" and "naphthalene charge stock", and a fuel derived from shale oil crude which was refined to Jet A specifications. Three CF6-50 engine size combustor types were evaluated; the standard production combustor, a Radial/Axial Staged Combustor, and a Double Annular Combustor. Performance and pollutant emissions characteristics at idle and simulated takeoff conditions were evaluated in a full annular combustor rig. Carboning and flashback characteristics at simulated takeoff conditions were evaluated in a 12° sector combustor rig.

¹ Kittredge, G.D., and Streets, W.L., "Gas Turbine and Jet Engine Fuels," Summary Report Navy Contract NOas 60-6009-C, Phillips Petroleum Co. Res. Div. Report 2760¹-60R, Feature No. 6040, 1960.

Cooperative tests conducted by Phillips, Navy Aeronautical Engine Laboratory and others exploring the role of fuel composition on flame radiant heating of jet combustor metal surfaces have indicated an almost linear relationship between total flame radiant heat emission from J-57 single combustor flames at about 5 atmospheres pressure and metal temperatures along the combustor liner. JP-5 fuel blends of constant smoke point containing polycyclic as opposed to monocyclic aromatic compounds produced somewhat more intense radiant heating in the J-57 combustor. Phillips Microburner tests at atmospheric pressure showed no differences in flame radiation among these fuels; however, in terms of combustion zone deposits JP-5 blends containing polycyclic aromatics performed somewhat more poorly at any given smoke point level than those containing only monocyclic aromatic compounds.

² Kittredge, G.D., "Gas Turbine and Jet Engine Fuels," Progress Report No. 1, Navy Contract NOas 60¹-6009-C, Phillips Petroleum Co. Res. Div. Report 2508¹-59R, 1959.

Effects of monocyclic versus polycyclic aromatic structures in JP-5 fuels of equal ASTM Smoke Point level were studied using full scale and laboratory scale single combustors along with several bench scale lamp test procedures.

Results with a single J57 combustor operated at a pressure approaching 5 atmospheres showed very measurable differences in flame radiant heating of the combustor liner surface due to variations in fuel composition. Blends containing polycyclic aromatics had somewhat more adverse effects

than equal smoke point blends with monocyclic aromatics. Visual brightness of the J57 combustor flames was only a rough guide to total radiant heat emitted.

The Phillips 2-inch combustor flame radiation intensities at 5 atmospheres pressure correlated quite well with the J57 results, though the adverse effects of polycyclic aromatics were not "seen" by the 2-inch combustor at this condition. In contrast, the 2-inch combustor tests at 15 atmospheres pressure correlated much less well with the J57 results, but here the polycyclic aromatics (on an averaged basis) did show up more poorly than the monocyclic aromatic compounds.

Tests at close to 1 atmosphere pressure in a J79 full scale single combustor and in the Phillips Microburner showed no significant differences between any of the fuels tests in flame radiant heating effects. However somewhat heavier microburner deposit laydown was observed with the polycyclic aromatic blends.

Three bench scale lamp test procedures, ASTM Smoke Point, Standard of Indiana Smoke Point and CRC Luminometer, all agreed in general with the trends shown in the J57 combustor. The latter two procedures would accomodate the complete range in fuel quality represented by these test fuels and, in addition, appeared slightly more sensitive to polycyclic aromatics.

4. Kuhbach, C.M., Ritcheske, W.F., and Strauss, K.H., "Properties and Jet Engine Combustor Performance," SAE Paper presented at the SAE National Aeronautic Meeting Los Angeles, Volume 63, 1955.

Studies of deposit formation in jet engines indicate that:

1. No single number can describe completely the severity of deposits.
2. Location and magnitude of deposits depend on combustor design.
3. Combustors can be designed so that they are tolerant of wide ranges of fuel volatility and composition.
4. Deposit weight is a fairly good indication of fuel cleanliness, if deposits from several fuels used in the same engine are compared.
5. Light deposits may cause more trouble than heavy ones, if the former are formed at critical spots.
6. Deposits predictions based on fuel properties or simple burning tests are not always reliable because fuels do not behave the same in different combustors.
7. At first, deposits build up in direct proportion to running time. Later, the buildup rate begins to fall off until, finally, the deposit level becomes constant.
8. The early rate is a better indication of fuel cleanliness than is the equilibrium deposit level.
9. Deposits generally increase with decreasing fuel volatility (heavier fuels) and increasing degree of fuel unsaturation (more aromatics and olefins).

1 Macaulay, R.W., and Shaveson, M.W., "Effects of Fuel Properties on Liner Temperatures and Carbon Deposition in the CJ805 Combustor for Long-Life Applications," ASME 61-WA-304, Oct 1961.

Extensive flight test of the CJ80 engine has demonstrated durability characteristics for the combustor with fuels of marginal quality. Efforts to increase this durability by reducing liner temperatures and carbon deposition have resulted in improved designs. During the past two years, single-can combustion tests have been undertaken in a co-operative program with Texaco Research Center at Beacon, N.Y., to evaluate carbon formation and liner temperatures with various liquid fuels. These results have been correlated with factory engine tests and General Electric component combustion tests with resulting improvements in liner cooling and carbon formation.

1 Marchionna, N.R., et al., "Turbine Fuel Tolerance Study, Initial Engine Test: No. 4 Oil," USATARADCOM Technical Report No. 12272, April 1977.

An AGT 1500 vehicular gas turbine engine was operated on No. 4 residual oil using a specially modified combustor. Problem areas encountered include coke buildup in the combustor, particularly at low power.

1 Marchionna, N., "Turbine Fuel Tolerance Study; Multifuel Engine Tests," USATARADCOM Technical Report 12392, (USATARADCOM DAAEO7-74-C-0274), July 1978.

An AGT 1500 vehicular gas turbine engine was tested for multifuel capability. Overall performance did not vary when operating on JP-4, DF-2, or unleaded gasoline. Coke deposition occurred on the liner wall with No. 4 oil indicating that further development is required to provide coke free operation with this fuel for cool days and low power conditions.

1 Pillsbury, P.W., et al, "Fuel Effects in Recent Combustion Turbine Burner Tests of Six Coal Liquids," ASME 79-GT-137, March 1979.

Comparative tests have been made in combustion turbine burners between six coal derived liquid (CDL) fuels and No. 2 distillate oil. All CDL fuels were evaluated in a half-scale (by diameter) combustor test rig, while one CDL fuel was also evaluated in a full scale high pressure combustion rig. The effects of these fuels on emissions of smoke and oxides of nitrogen, and on combustor metal temperature are discussed. Also observed in the testing were flame radiation, post-test combustor cleanliness, and emissions of carbon monoxide and hydrocarbons. Two of the CDLs do appear to be within the tolerance band which present combustion turbines can accept, with the exception of elevated NO_x emissions.

1 Radowky, F.W., and Meguerian, G.H., "Precombustion Deposits," Combustion and Flame, 10, 182 (1966).

The processes governing deposit formation during vaporization of hydrocarbon mixtures in the presence of air have been studied by means of a continuous flow system. At about 400°C paraffinic hydrocarbons produce

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very little deposits. The amount of deposits increases and passes through a maximum as the volume of aromatics in the mixture is increased. The level of this maximum varies mainly with the volatility of the aromatic. According to the mechanism suggested, paraffinic radicals produced by the interaction of paraffins and oxygen react with aromatic hydrocarbons to generate aromatic radical. These relatively stable radicals then diffuse to the reactor wall, are adsorbed, and polymerize to produce deposits. The best method of minimizing deposit build-up of this type is to prevent condensation. In vaporizing burners, vapours should be burned as soon as possible after vaporization and should not be allowed to contact cool surfaces.

1 Roberts, R., Peduzzi, A., and Vittti, G.E., "Experimental Clean Combustor Program, Phase II, Alternate Fuels Addendum," NASA CR-134970, July 1976.

An Alternate Fuels investigation was conducted as an addendum to Phase II of the NASA Experimental Clean Combustor Program. The objective was to experimentally determine the impacts, if any, on exhaust emissions, performance, and durability characteristics of the Hybrid and Vorbix low-pollution combustor concepts when operated on test fuels which simulate composition and property changes which might result from future broadened aviation turbine fuel specifications or use of synthetically derived crude feedstocks. Severe carbon deposition was observed in both combustors following limited endurance testing with No. 2 Home Heat fuel.

1 Robson, K., "The Influence of Changing Fuel Specification on Combustor Performance and Emission: A Review of Derby Test Experience," Rolls-Royce Aero Division Derby Report DP 353, March 1979.

Carbon build up in flame tubes and subsequent turbine erosion is already a problem on some engines. The increase in flame carbon anticipated with revised fuel specification is likely to aggravate this. Testing aimed at measuring the extent of potential problems will be needed.

1 Schirmer, R.M., "Specification of Jet Fuel Hydrogen Content for Control of Combustion Cleanliness," Progress Report No. 1, Navy BuWep Contract N600(19)-58219, Phillips Petroleum Co. Research Div. Report 3195-62R, Feature No. 6049, 1962.

A critical analysis has been made of current test methods, Smoke Point and Luminometer Number, for evaluation of the burning quality of hydrocarbon fuels for aircraft gas turbine engines. Unfortunately, the laminar flow diffusion flame of the wick lamp differs appreciably from the highly turbulent combustion process in an aircraft gas turbine engine. Differences in the mechanism of soot formation, as evidenced by the effect of hydrocarbon structure, are discussed in detail. This can result in undue emphasis being placed upon the attainment of a jet fuel quality, such as a very high Luminometer Number, from which no significant benefit in terms of performance or durability can reasonably be expected.

Measurements of the cleanliness of aircraft gas turbine combustion processes, liner temperature and flame radiation, show a linear correlation

with hydrogen content of the fuel. The cleanest burning fuels are those that contain the most hydrogen. A two- to fourfold improvement in repeatability and a fourfold improvement in reproducibility over current test methods should be feasible with hydrogen content. The use of hydrogen content for specification of jet fuel burning quality is recommended.

Streets, W.L., "Characteristics of Flame Radiation of High Temperature Hydrocarbon Fuels," Phillips Petroleum Co. Research Division Report 2307-59R, Feature No. 6024, April 1959.

Investigation of the effects of monocyclic and several polycyclic hydroaromatic high temperature hydrocarbon fuels on flame radiation and flame tube metal durability has been conducted in a two-inch laboratory scale combustor under simulated conditions of sea-level takeoff, medium altitude cruising and high altitude loitering flight. Isoparaffinic and aromatic fuels were also included for reference purposes. Supplementary data obtained include deposition, smokiness, combustion efficiency, flame radiation in the Phillips Microburner and ASTM smoke point.

Combustor deposition occurred only at the simulated high altitude flight condition with only dimethano decalin rating outstandingly poor among the polycyclic fuels.

Sztela, E.J., "Deposits from Heated Gas Turbine Fuels," ASME 76-GT-9, 1976.

Deposits from gas turbine fuels are a major concern when prevaporized-premixed combustor concepts are considered for gas turbine engines. Even in conventional gas turbines, deposits are occasionally found in fuel nozzles after a long period of operation. A search was made for information regarding deposits from heated gas turbine fuels using open literature data and data generated within United Technologies Corporation. Summaries of both the data obtained from this survey and the physical and chemical mechanisms leading to the formation of fuel deposits are presented. Data obtained by Pratt and Whitney Aircraft at the Florida Research and Development Center indicate that deposits were suppressed while the fuel was vaporized by mixing with air at velocities of 6 to 13 fps (15 to 33 cm/sec) and pressures of 50 to 200 psis (3.4 to 14 atm). Data obtained at United Technologies Research Center showed that deposits can also be prevented by intermittent use of heated air. Data obtained at EXXON and at the Naval Research Laboratory show that although deposits increase with temperature, a peak is found at about 700 F (682 K). Fuel vaporization was shown to increase the deposit levels in experiments at the Air Force Aero Propulsion Laboratory.

Vogel, R.E., Troth, D.L. and Verdouw, A.J., "Fuel Character Effects on Current, High Pressure Ratio, Can-Type Turbine Combustion Systems," Air Force Aero Propulsion Laboratory Report No. AFAPL-TR-79-2072, Feb 1980.

The effect of limited fuel property variation on the performance of current, high pressure ratio can-type combustors was evaluated. The TF41 turbofan combustor was employed. This combustor has conventional dual-orifice fuel injection and film cooling. The combustion zone is

approximately stoichiometric at takeoff. Twelve experimental fuels, including JP-4 and JP-8, were tested. Boiling range hydrogen content, and aromatic type were varied by blending JP-4 and JP-8 fuel with mineral seal oil and two types of aromatic solvents. Fuel hydrogen content varied from 14.5% to 12%. Performance tests were accomplished at idle, altitude cruise, dash, and takeoff conditions. Sea level and altitude ignition tests were also completed. Fuel fouling and carboning characteristics were established.

Combustor operating parameters such as liner temperature, pattern factor, ignition fuel-air ratio, lean blowout fuel-air ratio, and exhaust emissions were correlated to fuel properties. The effect of fuel properties on combustor and turbine hardware durability was assessed analytically.

SECTION VI

Survey Papers or Papers Difficult to Classify Otherwise.

1 Angello, L.C., et al., "Shale Oil - The Answer to the Jet Fuel Availability Question," SAE Paper No. 781027, 1978.

The cost of jet fuel to the Air Force has increased greatly since the 1973 oil embargo. The bill in 1973 was slightly over one-half billion dollars for 112 million barrels of JP-4, whereas, it is now approximately 1.6 billion dollars or about 6 percent of the Air Force annual budget for only 80 million barrels. This paper discusses an Air Force program which will result in adequate fuel availability for the Air Force at an acceptable cost. Results of recent processing studies on alternative hydrocarbon sources from shale oil are presented, together with combustor studies directed to determining the effects of property variations on combustor performance, durability and level of harmful emissions. A projection of the chemical and physical properties of the future Air Force aviation turbine fuel is presented.

2 Blazowski, W.S., and Henderson, R.E., "A Review of Turbopropulsion Combustion. Part 1: Fundamentals of Combustion. Part 2: Turbopropulsion Combustion Technology," Summary Report, Mar. 1975 - Dec. 1976. (AD-A043022; AFAPL-TR-77-41) Jun 1977.

This report constitutes a reprint of two chapters on turbopropulsion combustion expressly prepared as part of a propulsion Text Book entitled A Comprehensive Study of Aircraft Gas Turbine Engines, edited by G.C. Oates. A variety of subjects are reviewed ranging from fundamental chemistry, thermo-dynamics and gas dynamics of combustion to jet engine combustor design factors, performance characteristics and engineering/analysis tools. In addition, the impact of environmental controls and regulations is discussed and the effects alternate and/or non-spec fuels may have on combustion system performance are examined. Each chapter includes an extensive reference list of related topics many of which expand further on key points discussed.

3 Blazowski, W.S., "Future Jet Fuel Combustion Problems and Requirements," Progress in Energy and Combustion Science, Oct 1977.

A complex program is necessary to establish the information base from which future fuel specifications can be made. Fuel processing technology will naturally be of primary importance to per-gallon fuel costs. The impact of reduced levels of refining (lower fuel costs) on all aircraft system components must be determined. These include fuel system (pumps, filters, heat exchangers, seals, etc.), and airframe (fuel tank size and design, impact on range, etc.) considerations as well as main burner and afterburner impacts. In addition, handling difficulties (fuel toxicity) and environmental impact (exhaust emissions) require evaluation. The overall program must be integrated by a system optimization study intended to identify the best solution to the stated objectives.

This paper focuses on information relating to the combustion system aspects of the tradeoff. Specifically, it is intended to define the problems to be encountered and identify future directions to be undertaken in combustion research. The paper is written with sufficient background information to allow researchers not familiar with gas turbine combustion systems to understand the problems faced and the areas requiring further study.

The following major sections are concerned with descriptions of jet fuel characteristics and requirements, the gas turbine combustion system, fuel effects on combustion system operation, and future R&D requirements.

↳ Bowman, C.T., and Birkeland J., Alternative Hydrocarbon Fuels: Combustion and Chemical Kinetics; SQUID Workshop, Loyola College, Columbia, Md., September 7-9, 1977, Technical Papers. American Institute of Aeronautics and Astronautics, Inc, New York (Progress in Astronautics and Aeronautics Volume 62), 1978.

The considered topics are related to alternative fuel availability and anticipated combustion problems, critical processes in the combustion of alternative fuels, pyrolysis and oxidation kinetics of alternative fuels, pollutant emissions considerations for alternative fuel combustion, and questions of alternative fuels policy and technology. Attention is given to alternative fuels and combustion problems, future fuels in gas turbine engines, alternative fuels for reciprocating internal combustion engines, the use of alternative fuels in stationary combustors, alternative fuels in gas turbine combustors, combustion and chemical kinetics problems in internal combustion engines, the combustion of droplets and sprays of some alternative fuels, flame emissivities in the case of a use of alternative fuels, the pyrolysis and oxidation of aromatic compounds, the combustion chemistry of chain hydrocarbons, liquid-phase reactions of vaporizing hydrocarbon fuels, the role of aromatics in soot formation, the kinetics of nitric oxide formation in combustion, and emission control techniques for alternative fuel combustion.

↳ DeGreef, J.L., Maes, P., and Johnson, K.W., "Operating Experience on Residual Fuel Oil with a W251 Combustion Turbine," ASME Paper 78-GT-104, April 1978.

This paper describes the actual operating experience of a current technology combustion turbine, burning residual fuel, operating under actual utility conditions. The objective of the program was to demonstrate that combustion turbines utilizing air-cooled blades and vanes were capable of performing in an economical, reliable and satisfactory manner to meet the demands of a utility company in normal daily cyclical duty. Included in the program was an evaluation of fuel treatment plant with associated fuel-handling requirements, resistance to corrosion of numerous blade and vane alloys both with and without protective coatings, plus optimization of a turbine cleaning system to remove turbine blade path deposition.

↳ Felix, P.C., "Problems and Operating Experiences with Gas Turbines Burning Residual and Crude Oils," ASME Paper 78-GT-103, April 1978.

This paper presents the most important problems which have to be expected when burning residuals and crudes in industrial gas turbines. Solutions for these problems are always influencing the operating costs of the powerplant. Careful economical studies should, therefore, be conducted before one or another fuel is selected. Finally, operating experiences with 14 BBC gas turbines located in Riyadh (Kingdom of Saudi Arabia) burning local Khurais crude oil with turbine inlet temperatures of 650 to 850 C are presented.

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Frieder, A.J., Felix, P.C., and Hess, H.J., "Experiences with Gas Turbines Burning Non-Refined Fuel Oils and Related Theoretical Investigations," ASME Paper 74-GT-12, March 1974.

This paper presents experience on large, low firing temperature European gas turbine operating on crude and residual fuels. The most economic fuel can be a distillate, a heavy distillate, a crude oil, and, in some applications, even a residual fuel.

1. Grobman, J., "Alternative Aircraft Fuels Technology," NASA SP-416. Presented at NASA Conference on Aircraft Safety and Operating Problems; Langley, VA October 1976. p. 457-468.

NASA is studying the characteristics of future aircraft fuels produced from either petroleum or nonpetroleum sources such as oil shale or coal. These future hydrocarbon based fuels may have chemical and physical properties that are different from present aviation turbine fuels. This research is aimed at determining what those characteristics may be, how present aircraft and engine components and materials would be affected by fuel specification changes, and what changes in both aircraft and engine design would be required to utilize these future fuels without sacrificing performance, reliability, or safety. This fuels technology program has been organized to include both in-house and contract research on the synthesis and characterization of fuels, component evaluations of combustors, turbines, and fuel systems, and, eventually, full-scale engine demonstrations. The entire effort has been integrated with a similar program being conducted by the Air Force Aero Propulsion Laboratory (AFAPL) and is being coordinated with other government agencies within the DOD and ERDA. This paper is a review of the various elements of the program and presents significant results obtained so far.

2. Grobman, J.S., et al., "Alternative Fuels," NASA Conference Publication 2021. Presented at NASA Aircraft Engine Emissions Conference, Lewis Research Center, Cleve., May 1977. p. 277-308.

Potential problems related to the use of alternative aviation turbine fuels are discussed and both ongoing and required research into these fuels is described. This discussion is limited to aviation turbine fuels composed of liquid hydrocarbons. The advantages and disadvantages of the various solutions to the problems are summarized. The first solution is to continue to develop the necessary technology at the refinery to produce specification jet fuels regardless of the crude source. The second solution is to minimize energy consumption at the refinery and keep fuel costs down by relaxing specifications.

3. Grobman, J., "Impact of Broad-Specification Fuels on Future Jet Aircraft." NASA Conference Publication 2036 Part I. Presented at NASA CTOL Transport Technology Conference, Langley Research Center, Langley, VA., Feb. 1978. p. 217-233.

The effects that broad specification fuels have on airframe and engine components were discussed along with the improvements in component technology required to use broad specification fuels without sacrificing performance, reliability, maintainability or safety.

4. Longwell, J.P., and Grobman, J., "Alternative Aircraft Fuels," NASA TM-73836, ASME Paper No. 78-GT-59. Presented at Twenty-third Annual International Gas Turbine Conference sponsored by ASME, London, England, April 1978.

The efficient utilization of fossil fuels by future jet aircraft may necessitate the broadening of current aviation turbine fuel

specifications. The most significant changes in specifications would be an increased aromatics content and a higher final boiling point in order to minimize refinery energy consumption and costs. These changes would increase the freezing point and might lower the thermal stability of the fuel, and could cause increased pollutant emissions, increased combustion liner temperatures, and poorer ignition characteristics. This paper discussed the effects that broadened specification fuels may have on present-day jet aircraft and engine components and the technology required to use fuel with broadened specifications.

- Rudey, R.A., "The Long Term Energy Problem and Aeronautics." NASA SP-372, Presented at NASA/University Conference on Aeronautics, University of Kansas, Lawrence, Kansas, Oct 1974. p. 183-210.

The projected increase in energy consumption by transportation in general and civil aviation in particular is directly opposed to the dwindling supplies of natural petroleum crude oil currently used to produce aircraft fuels. This fact dictates the need to develop even more energy conservative aircraft and propulsion systems than are currently available and to explore the potential of alternative fuels to replace the current petroleum derived hydrocarbons. Advances in technology are described in the areas of improved component efficiency, aircraft and engine integration control systems, and advanced lightweight materials that are needed to maximize performance and minimize fuel usage. Also improved turbofan and unconventional engine cycles which can provide significant fuel usage reductions are described. These advancements must be accomplished within expected environmental constraints such as noise and pollution limits. Alternative fuels derived from oil shale and coal are described, and the possible technological advancements needed to use these fuels in aircraft engines are discussed and evaluated with relation to potential differences in fuel characteristics.

- Rudey, R.A., and Grobman, J.S., "Impact of Future Fuel Properties on Aircraft Engines and Fuel Systems," NASA TM-78866, AGARD Lecture Series 96, Oct 1978.

From current projections of the availability of high-quality petroleum crude oils, it is becoming increasingly apparent that the specifications for hydrocarbon jet fuels may have to be modified. The problems that are most likely to be encountered as a result of these modifications relate to engine performance, component durability and maintenance, and aircraft fuel-system performance. The effect on engine performance will be associated with changes in specific fuel consumption, ignition at relight limits, and exhaust emissions. Durability and maintenance will be affected by increases in combustor liner temperatures, carbon deposition, gum formation in fuel nozzles, and erosion and corrosion of turbine blades and vanes. Aircraft fuel-system performance will be affected by increased deposits in fuel-system heat exchangers and changes in the pumpability and flowability of the fuel. The severity of the potential problems is described in terms of the fuel characteristics most likely to change in the

future. Recent data that evaluate the ability of current-technology aircraft to accept fuel specification changes are presented, and selected technological advances that can reduce the severity of the problems are described and discussed.

¹ Rudey, R.A., and Grobman, J.S., "Characteristics and Combustion of Future Hydrocarbon Fuels." NASA TM-78865, AGARD Lecture Series 96, Oct 1978.

As the world supply of petroleum crude oil is being depleted, the supply of high-quality crude is also dwindling. This dwindling supply is beginning to manifest itself in the form of crude oils containing higher percentages of aromatic compounds, sulphur, nitrogen, and trace constituents. The result of this trend is described and the change in important crude oil characteristics, as related to aircraft fuels, is discussed. As available petroleum is further depleted, the use of synthetic crude oils (i.e., those derived from coal and oil shale) may be required. The principal properties of these "syncrudes" and the fuels that can be derived from them are described and discussed. In addition to the changes in the supply of crude oil, increasing competition for middle-distillate fuels may require that specifications be "broadened" in future fuels. The impact that the resultant potential changes in fuel properties may have on combustion and thermal stability characteristics is illustrated and discussed in terms ignition, soot formation, carbon deposition, flame radiation, and emissions.

¹ Rudey, R.A., "Effect of Broadened-Specification Fuels Systems," NASA TM 79086, 1979.

A wide variety of studies on the potential effects of broadened-specification fuels on future aircraft engines and fuel systems are summarized. The compositions and characteristics of aircraft fuels that may be derived from current and future crude-oil sources are described, and the most critical properties that may affect aircraft engines and fuel systems are identified and discussed. The problems that are most likely to be encountered because of changes in selected fuel properties are described; and the related effects on engine performance, component durability and maintenance, and aircraft fuel-system performance are discussed. The ability of current technology to accept possible future fuel-specification changes is discussed, and selected technological advances that can reduce the severity of the potential problems are illustrated.

A P P E N D I X A

MEMBERSHIP: PANEL ON FUEL QUALITY EFFECTS
ON COMBUSTION AND ENGINE PERFORMANCE AND DURABILITY

MEMBERSHIP

PANEL ON FUEL QUALITY EFFECTS ON COMBUSTION
AND ENGINE PERFORMANCE AND DURABILITY

C. A. Moses, Leader

J. A. Bert

W. Blazowski

C. C. Gleason

F. Humenik

T. A. Jackson

R. P. Lohmann

A. M. Mellor

A. S. Novick

G. Opdyke

Southwest Research Institute

Chevron Research Company

Exxon Research & Engineering Company

General Electric Company

NASA-Lewis Research Center

Air Force - Aero Propulsion Lab

Pratt & Whitney (Connecticut)

KVB, Inc.

Detroit Diesel Allison Division, GMC

AVCO-Lycoming

C. A. Moses and L. G. Dodge responsible for compilation
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